Compelling open and quantifiable questions that require next generation of RHIC:

From particles to fields in QCD

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The 2011 RHIC/AGS Users' Meeting
The RHIC/eRHIC Long Range Plan
Brookhaven National Laboratory

Disclaimer:

not a systematic representation of
the current/future RHIC program,
but a personal and biased view of a theorist

will not talk about pp program and spin - heavy ions only

Understanding QCD

QCD = quark model + gauge invariance

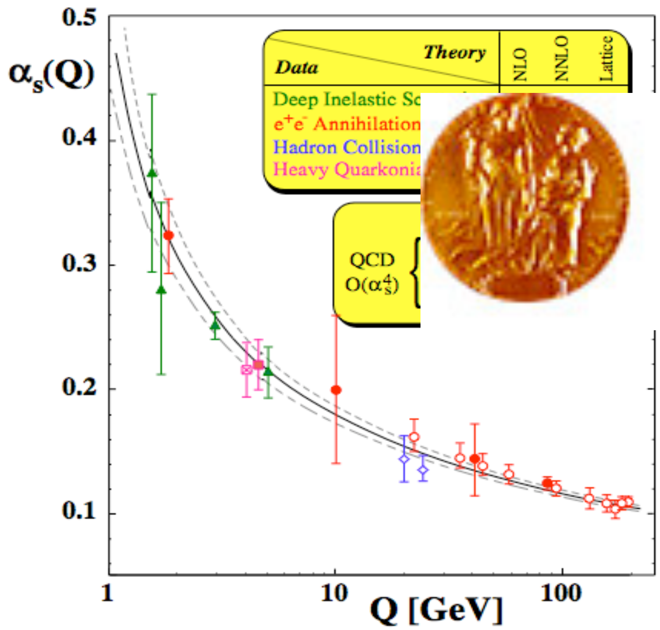
(FIELDS = GEOMETRY)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

Elegant, consistent, correct,
but not understood theory

Asymptotic Freedom: particles of QCD revealed



At short distances,
the strong force becomes weak
(anti-screening) -
one can access the "asymptotically free" regime in hard processes

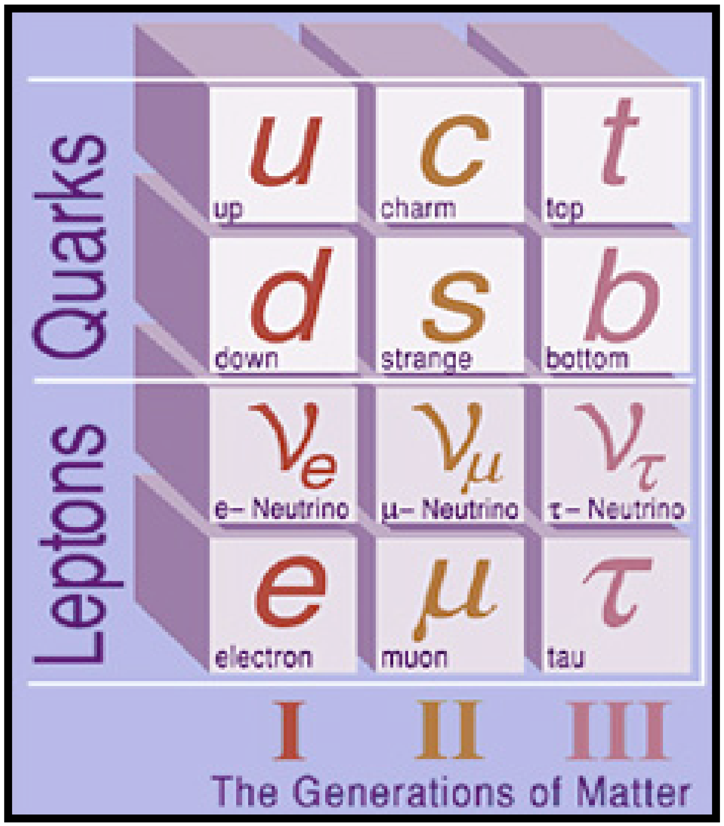
and in super-dense matter
(inter-particle distances ~ 1/T)

$$\alpha_s(Q) \simeq \frac{4\pi}{b \ln(Q^2/\Lambda^2)}$$

But: Strong confining interaction at large distances -
must understand dynamics of fields!

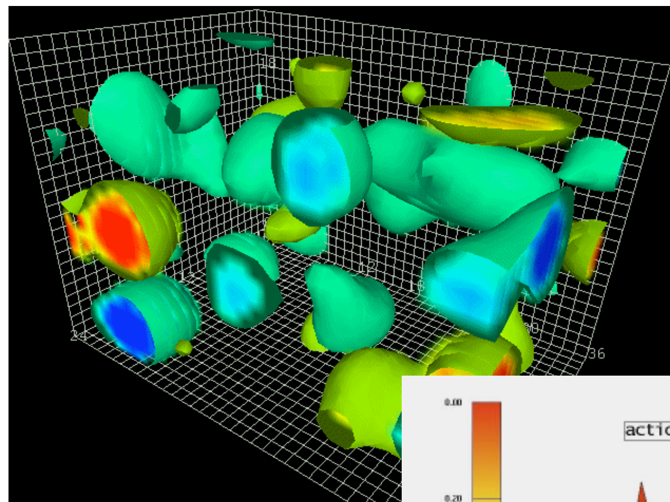
From particles to fields in QCD

Particles

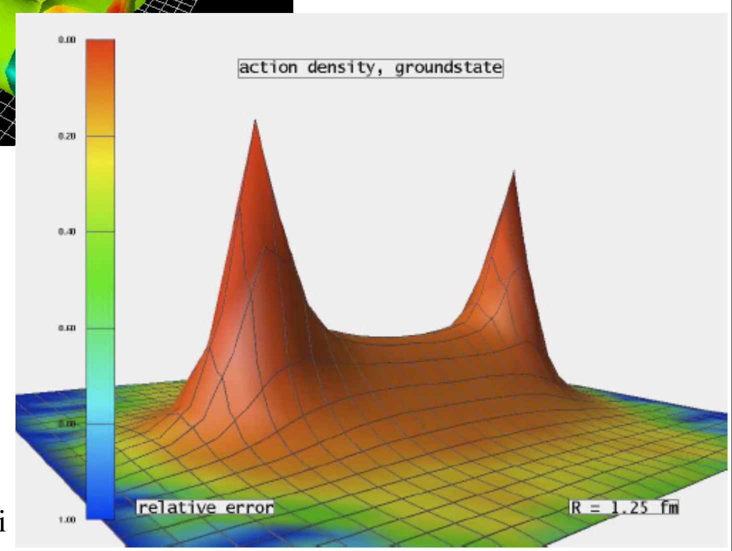


Fields

(Geometry)



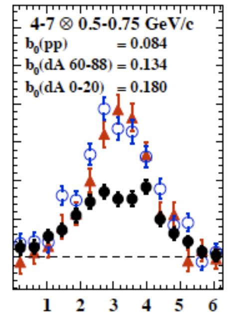
D. Leinweber

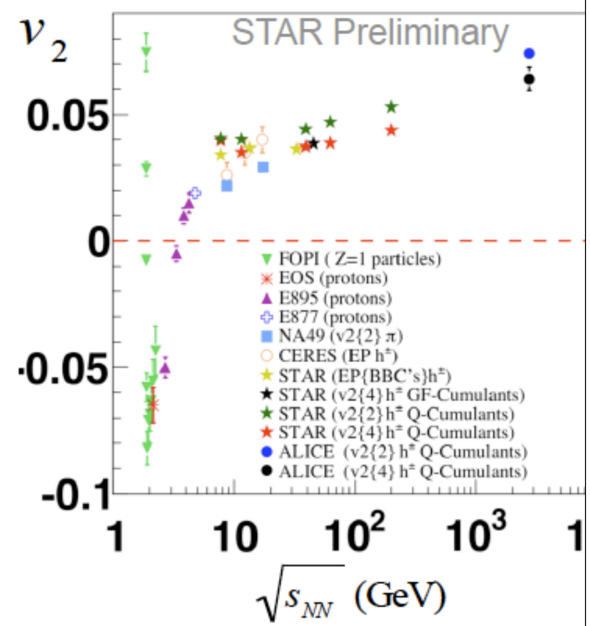


G. Bali

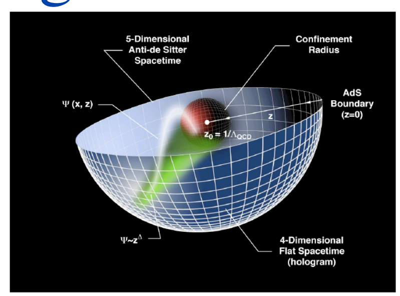
From particles to fields: collective phenomena as the essence of QCD

- From partons to strong color fields: nuclear wave functions at small x



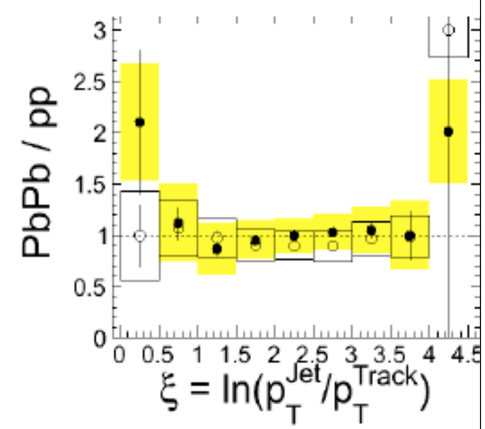


- Hydrodynamics and collective behavior: transport properties; phase diagram & fluctuations; anomalies and chiral magnetic effect



- Jets: the flow of energy and momentum in QCD

- The probes: heavy quarks, dileptons, ..

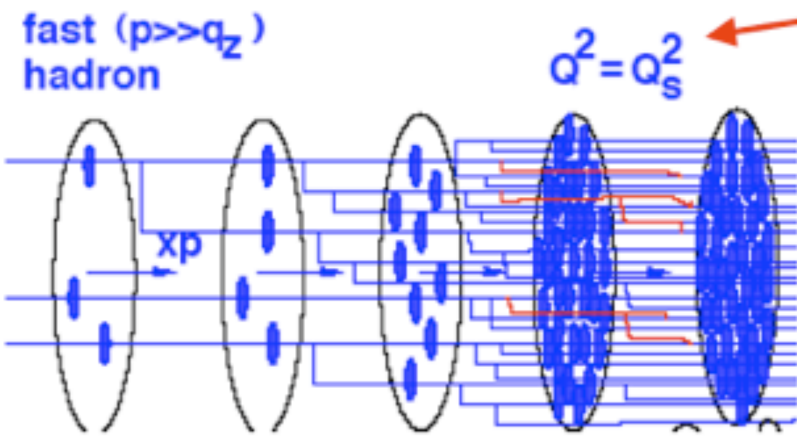


From partons to fields at small x

Bjorken x : the fraction of hadron's momentum carried by a parton; high energies s open access to small $x = Q^2/s$

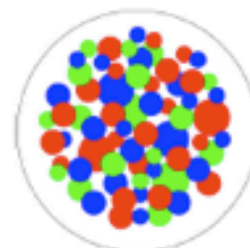
the boundary of non-linear regime: partons of size $1/Q > 1/Q_s$ overlap

Large x



Color Glass Condensate

small x

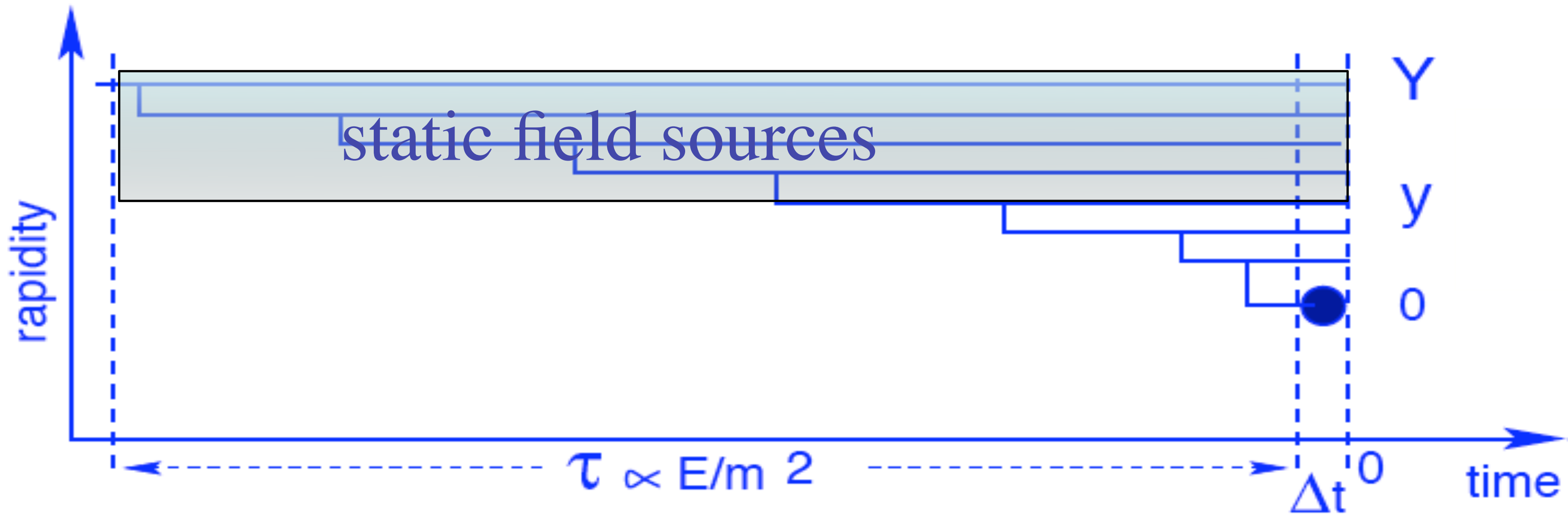


Because the probability to emit an extra gluon is $\sim \alpha_s \ln(1/x) \sim 1$, the number of gluons at small x grows; the transverse area is limited

→ transverse density becomes large

The origin of classical background field

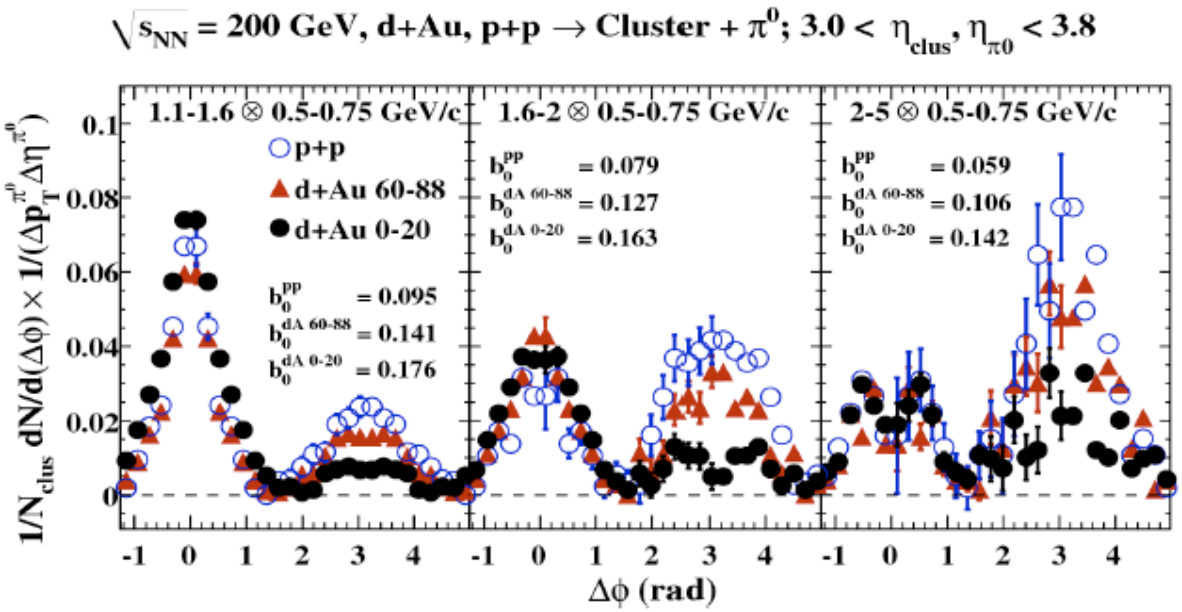
Coherent field with occupation number $\sim \dfrac{1}{\alpha_s(Q_s)}$
suppression of hard processes at small x;
depletion of back-to-back (quantum) correlations



Gluons with large rapidity and large occupation number act as a background field for the production of slower gluons

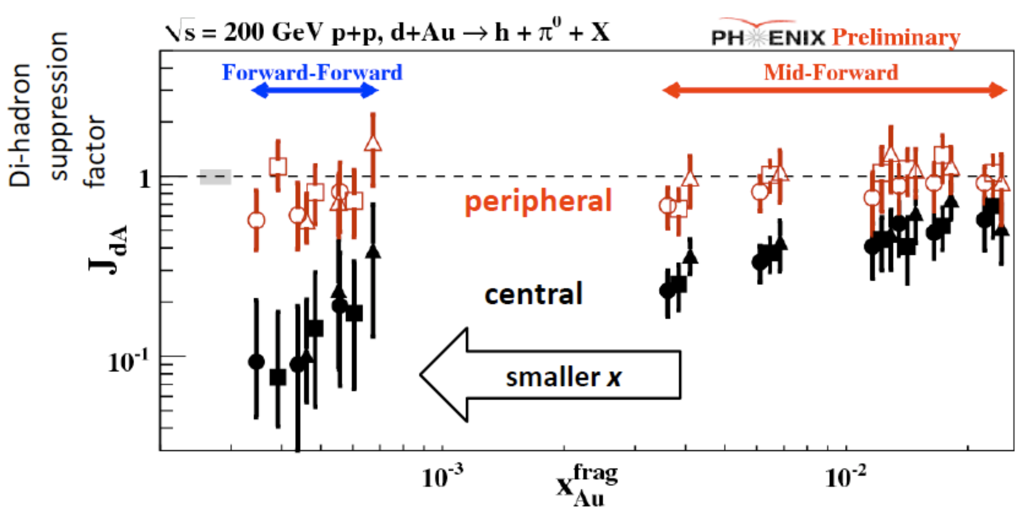
Color Glass Condensate

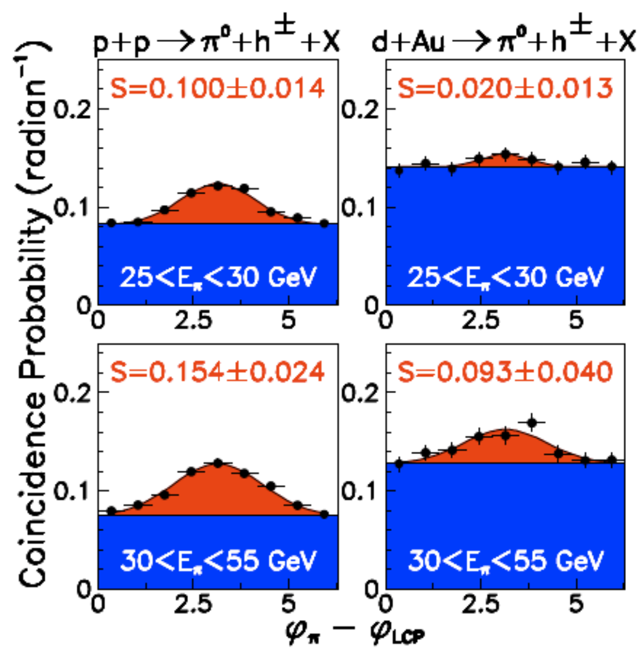
Probes of coherent gluon fields at small x



PHENIX Coll,
QM 2011
arXiv:1105.5112
Talks by
S.Bathe,
M.Chiu,
Z.Citron

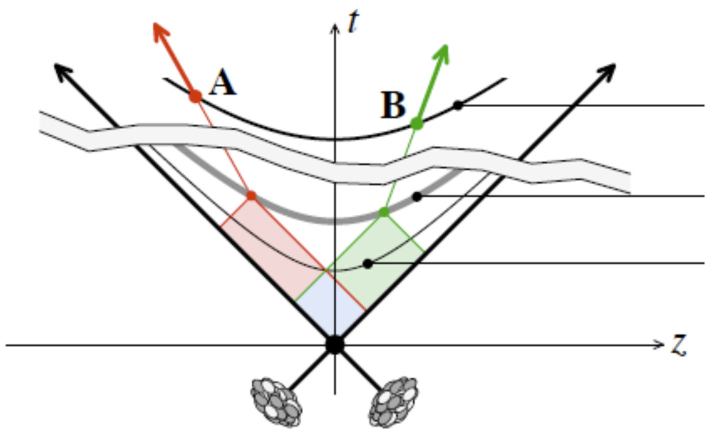
STAR Coll,
arXiv:0602011 (PRL)





Talk by M. Leitch

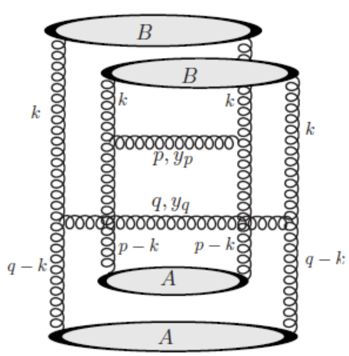
Probes of coherent gluon fields at small x: long-range correlations in rapidity

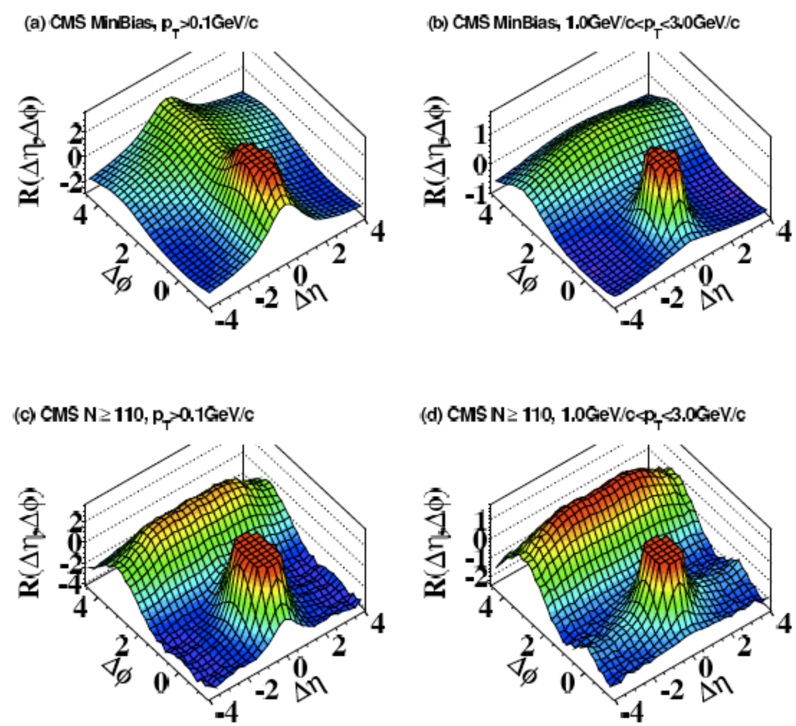


causality:

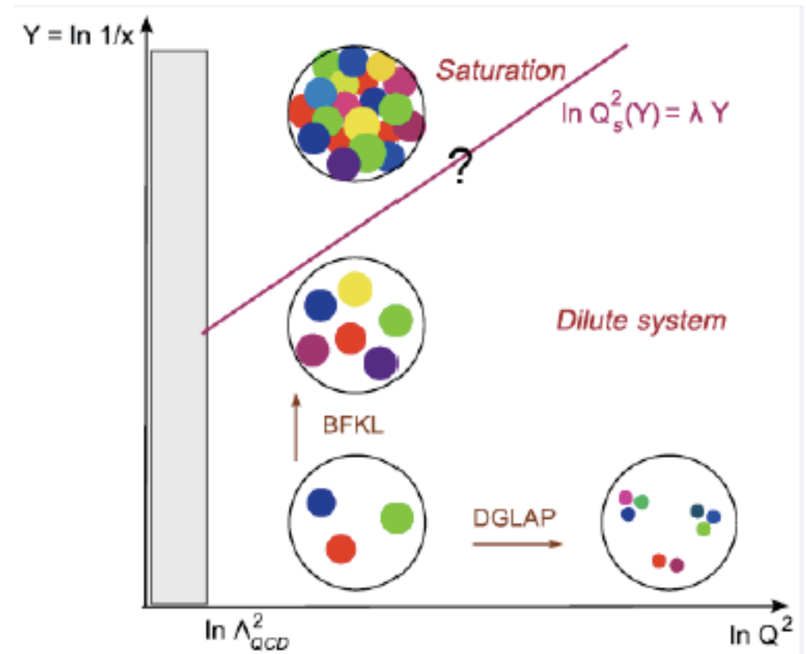
$$\tau_{\mathrm{init.}} = \tau_{\mathrm{f.o.}} \exp\left(-\frac{1}{2}\Delta y\right)$$

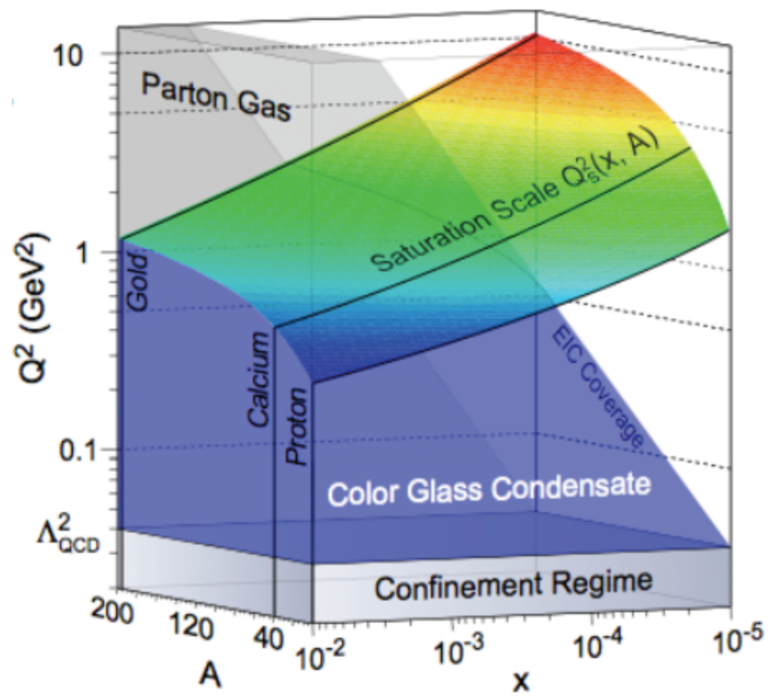
A.Dumitru, K. Dusling, F. Gelis,
J. Jalilian-Marian, T. Lappi, R. Venugopalan,
arXiv: 1009.5295





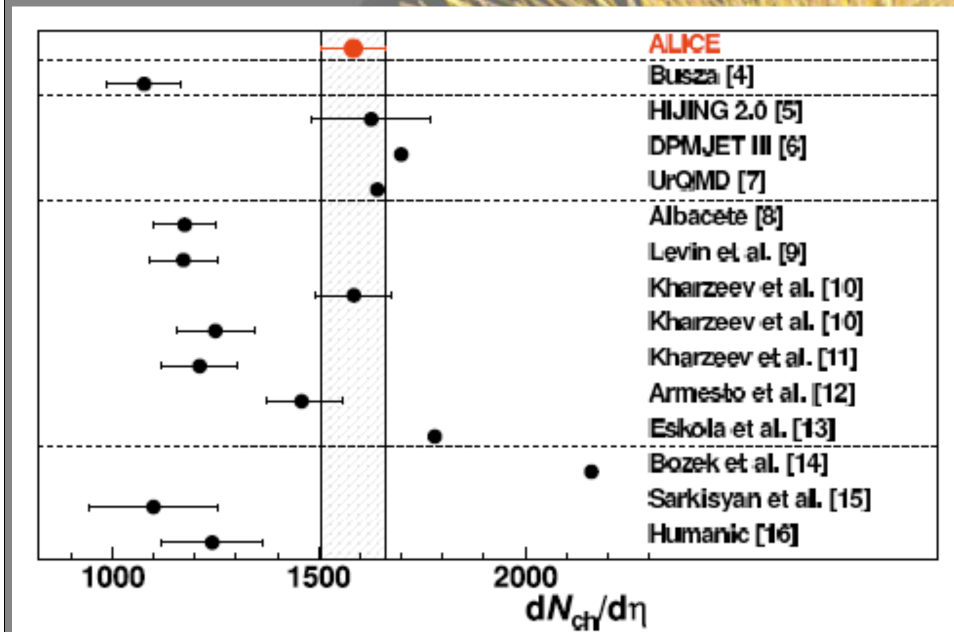
The path to eRHIC

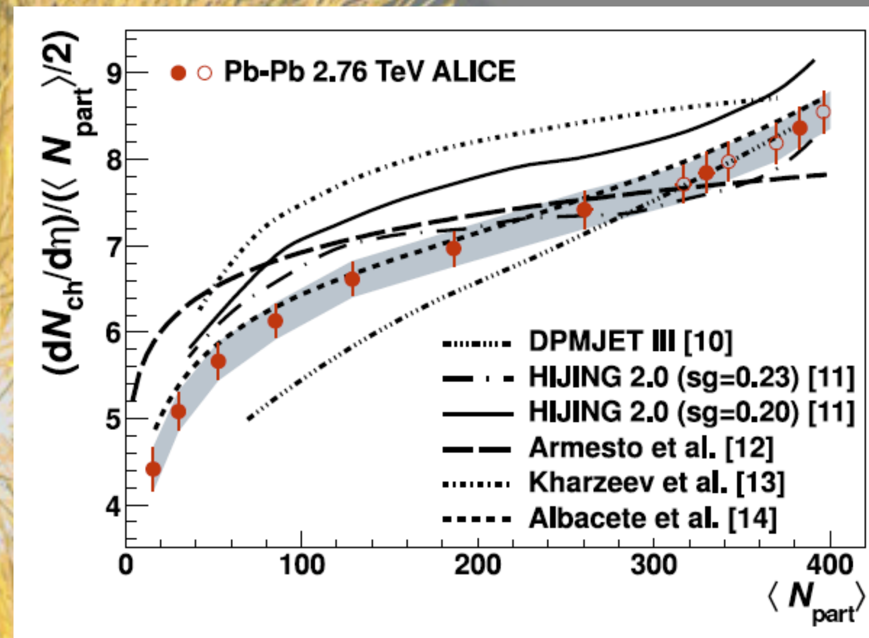




Dedicated session tomorrow

Breaking the coherence in nuclear collisions





Coherence of gluon fields inside the nuclei tames hadron multiplicities

ALICE

Pb+Pb @ sqrt(s) = 2.76 ATe

2010-11-08 11:30:46
Fill : 1482
Run : 137124
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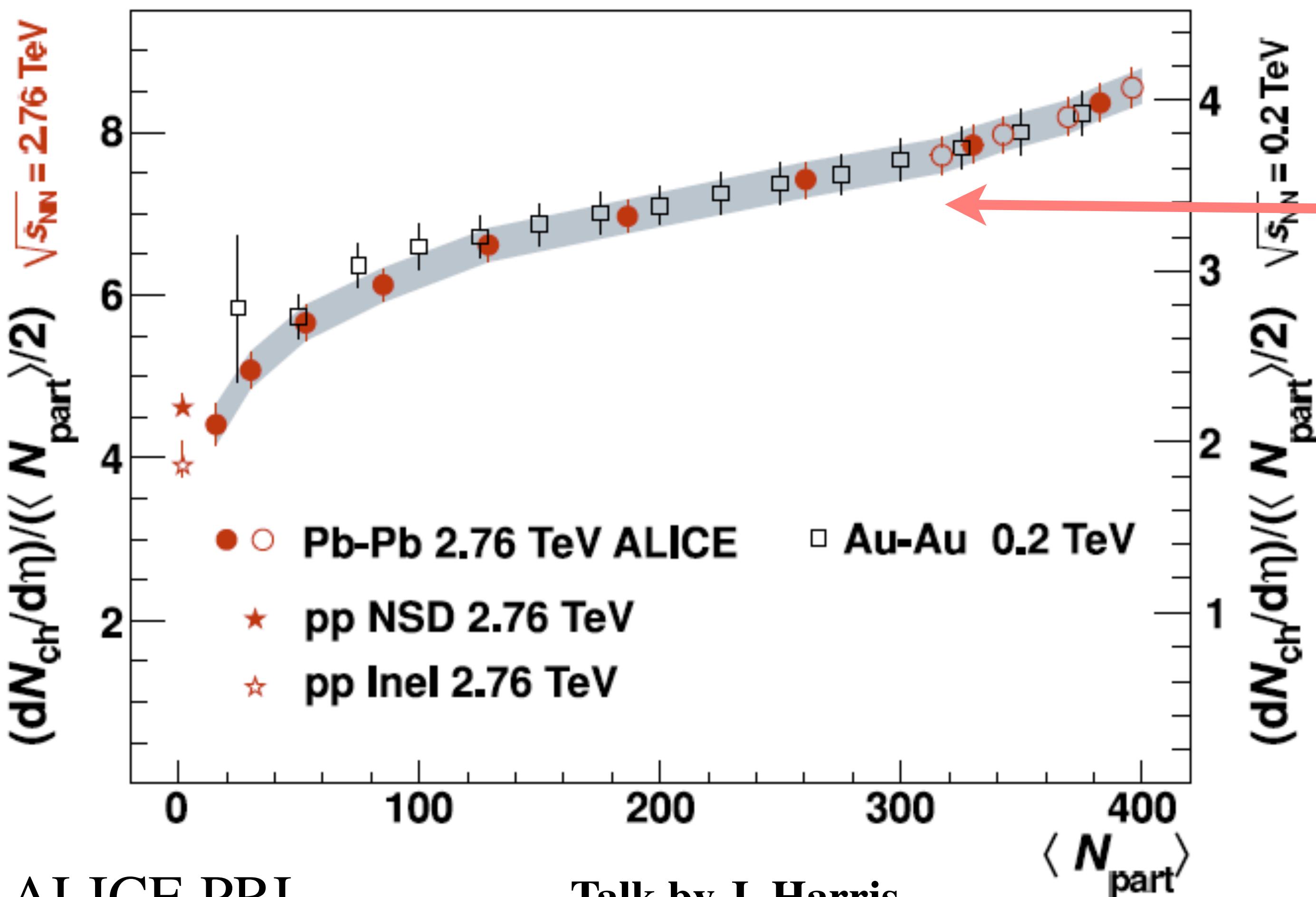
The scaling in the centrality dependence of hadron multiplicity at RHIC and LHC



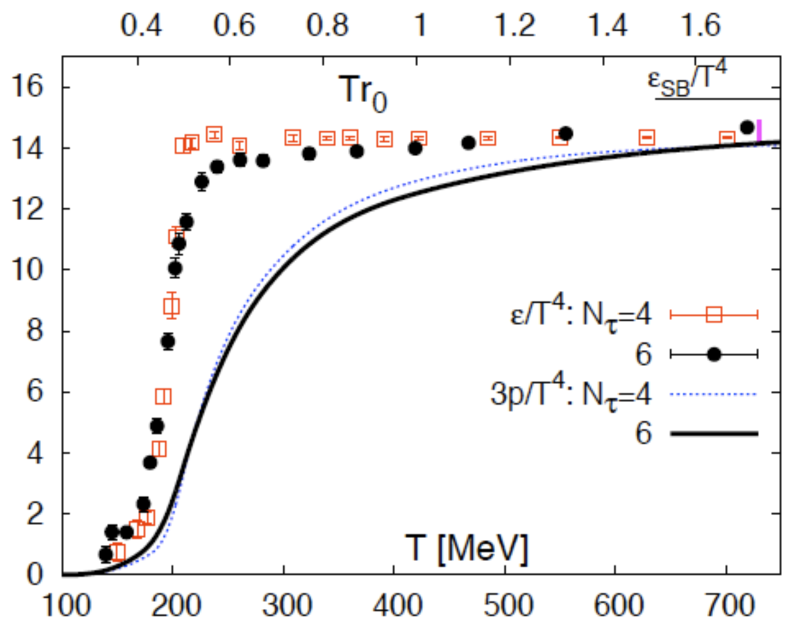
The origin of scaling within the parton saturation picture:

$$\sim \frac{1}{\alpha_s(Q_s)}$$

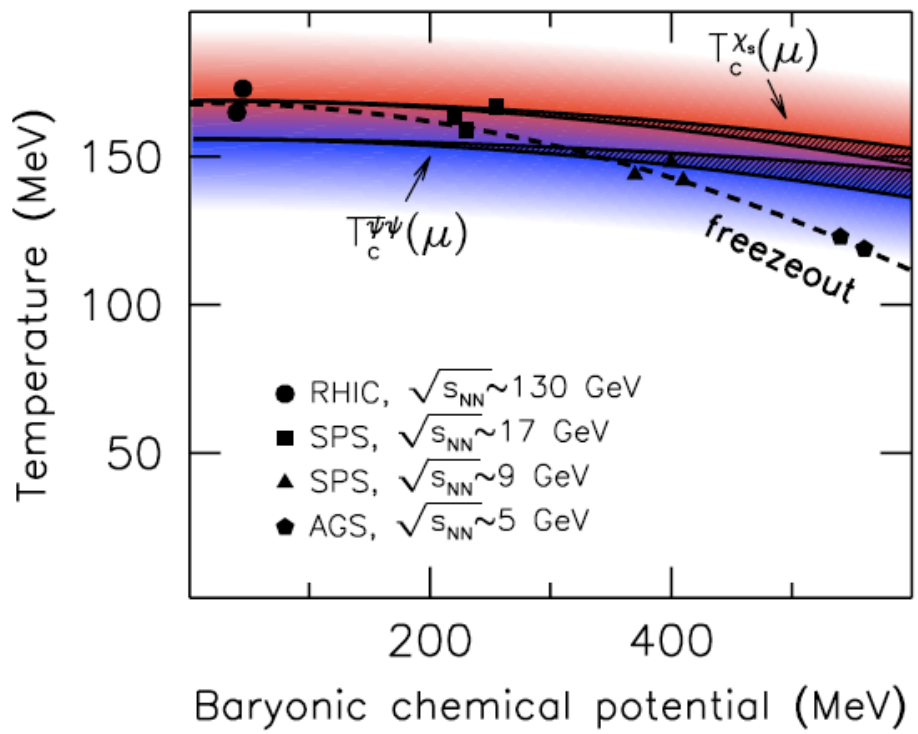
ALICE PRL

Talk by J. Harris

QCD at high energy density: gauge fields with boundary conditions (horizons)



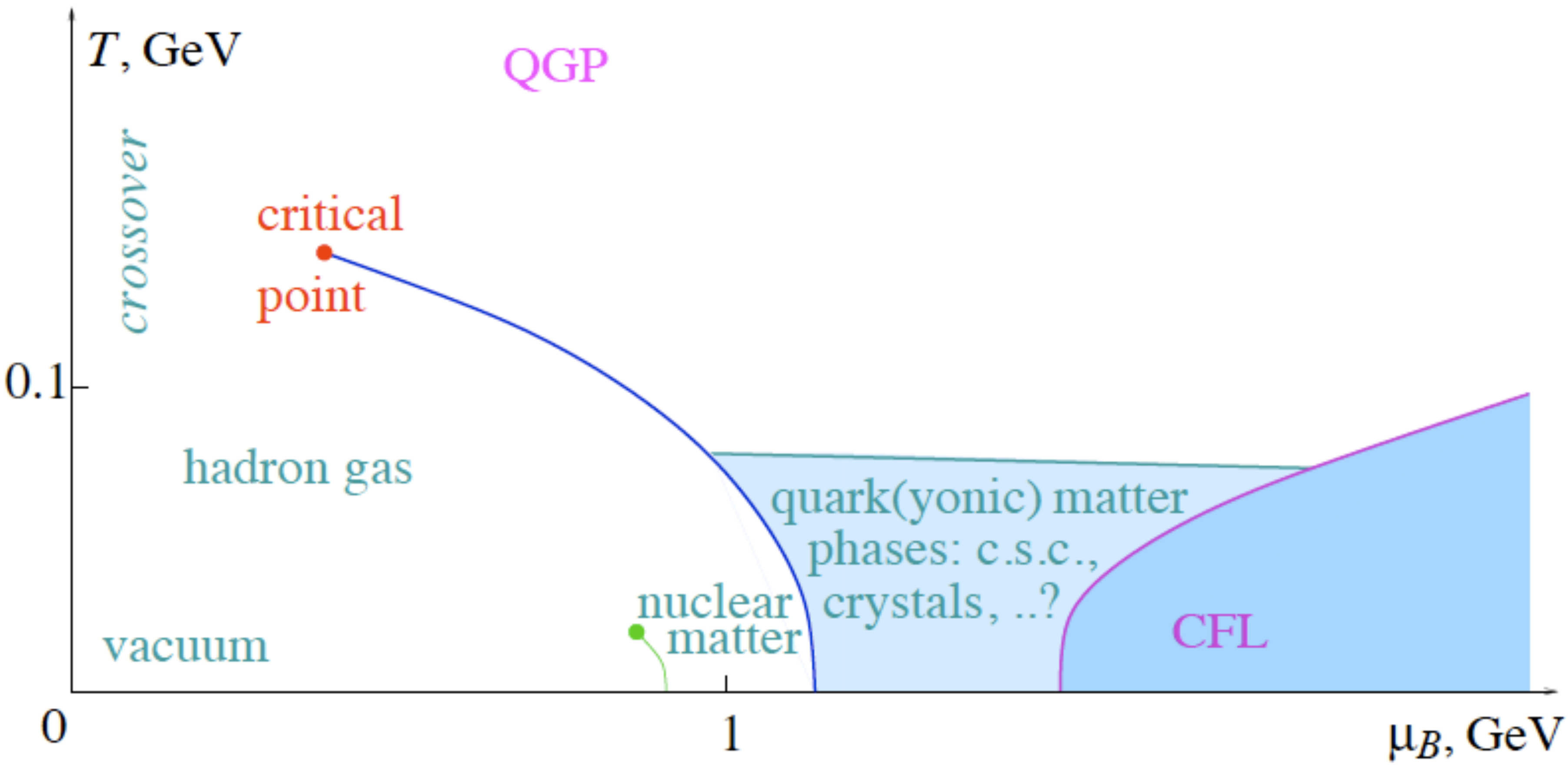
M. Cheng et al, arXiv:0710.0354



Talk by Z. Fodor

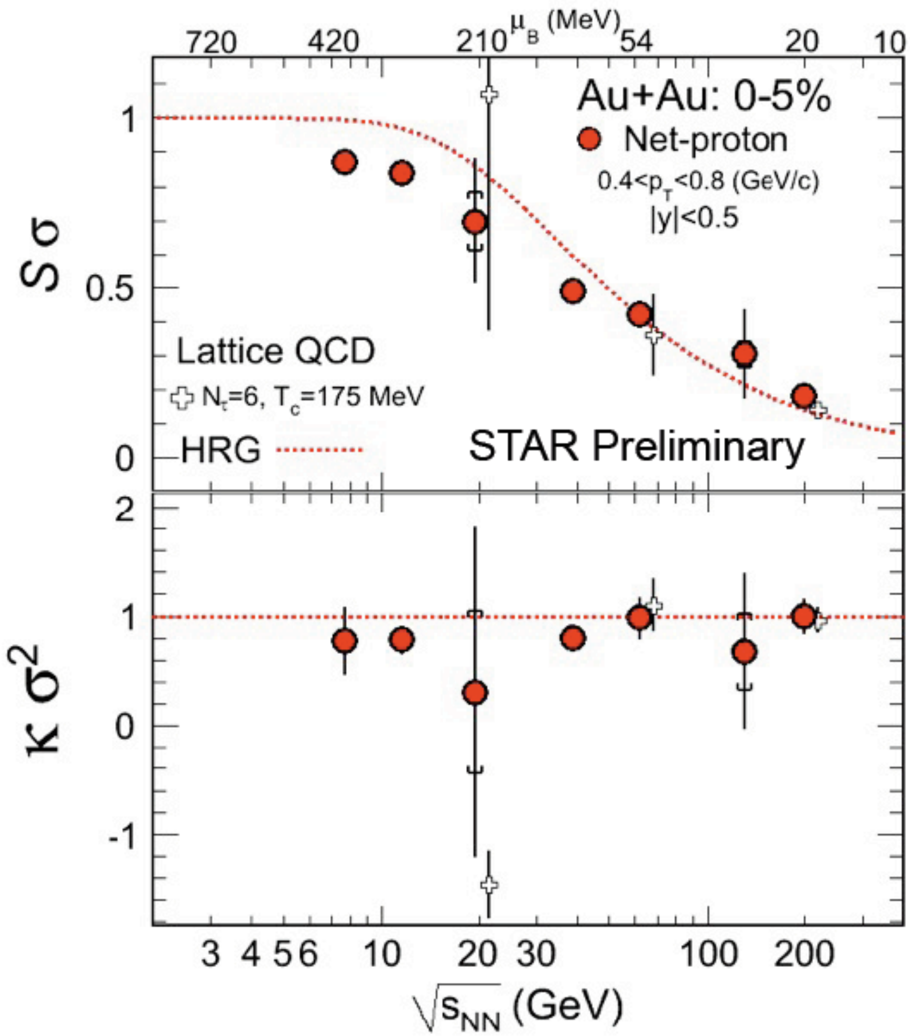
Is T~200 MeV "hot" or "cold"? The answer depends on the strength of interactions and gauge field dynamics

QCD phase diagram and the critical point



Talk by M. Stephanov

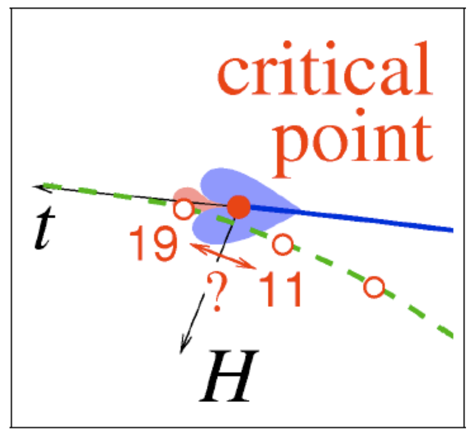
Search for the critical point in beam energy scan

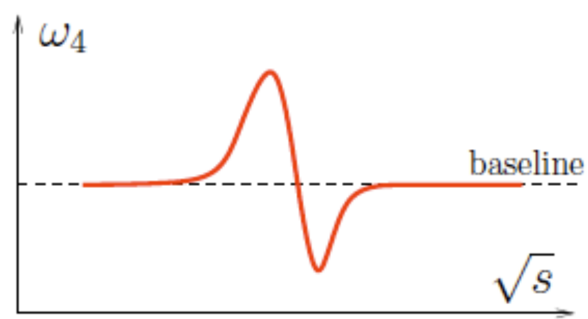


*19.6, 62.4 and 200 GeV: STAR, **PRL105**, 022302 (2010)*

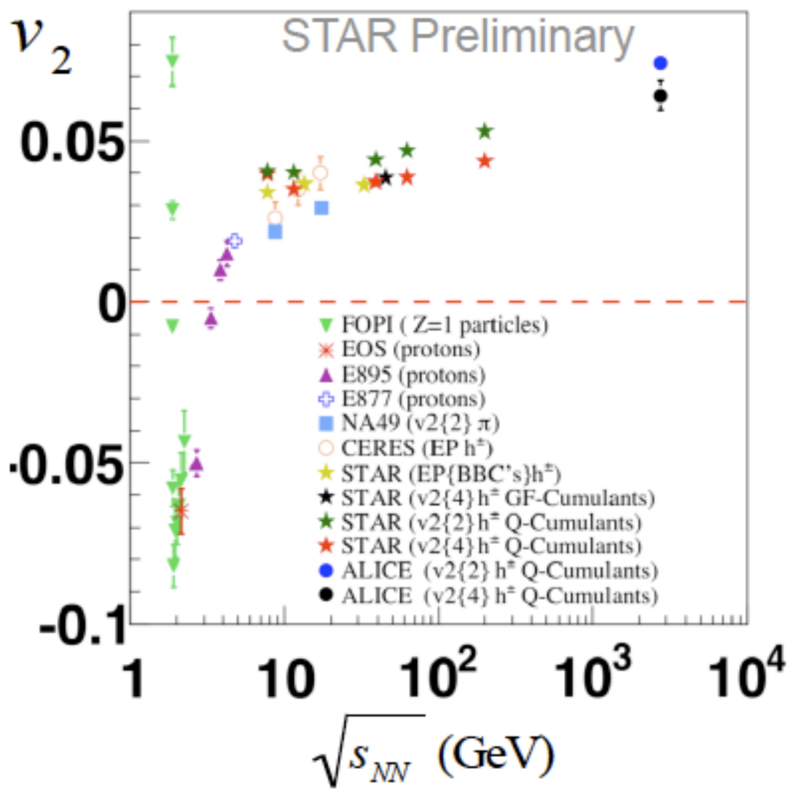
Talk by H. Masui (QM'11 + AUM'11)

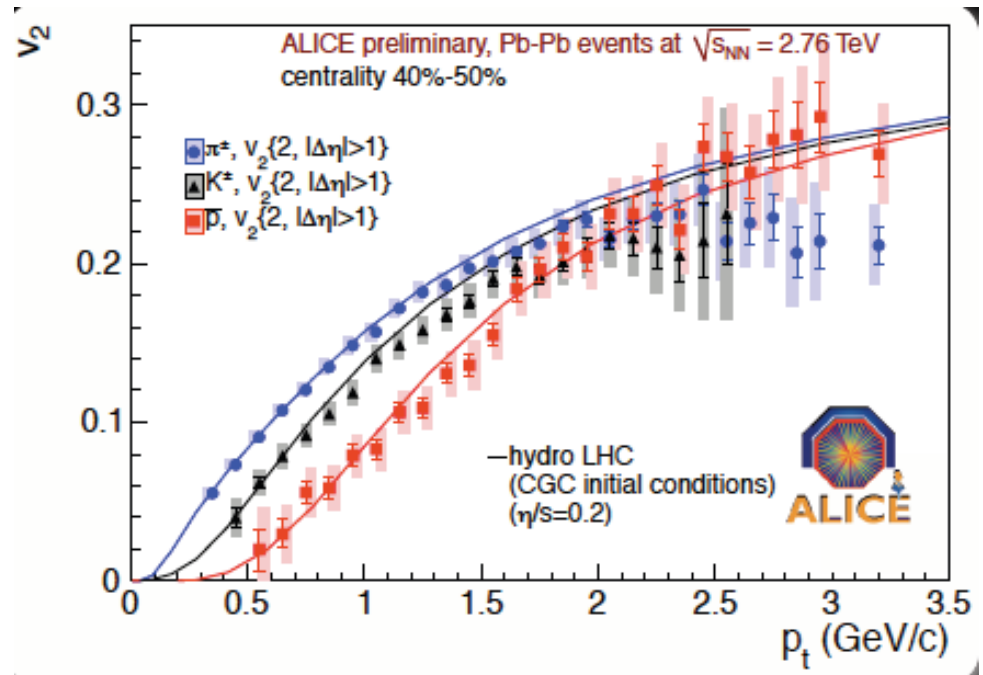
Talk by M. Stephanov



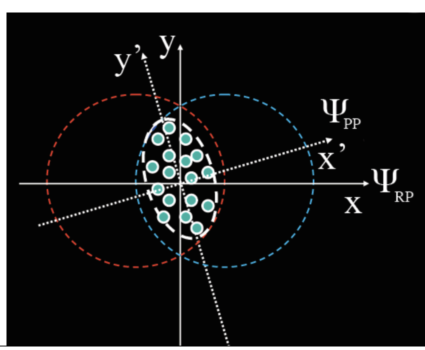


How does the produced matter evolve? The remarkable success of hydrodynamics





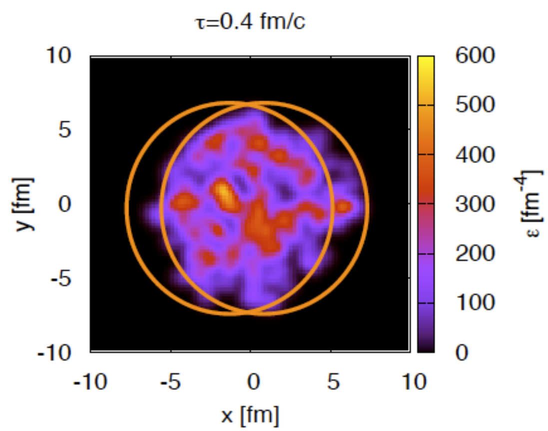
R. Snellings [ALICE Coll.] Talk at QM2011



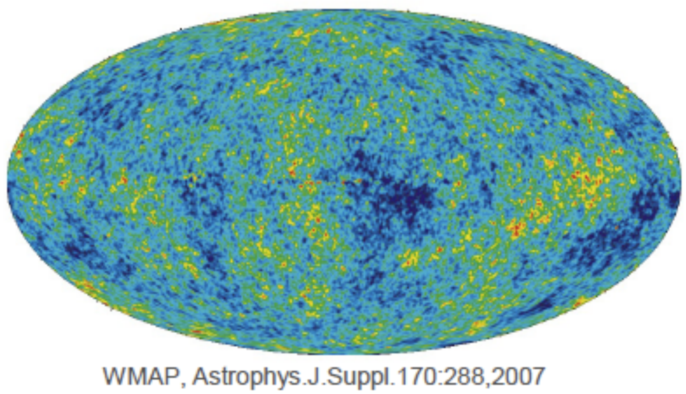
Talk by J. Harris

Hydrodynamics: an effective low-energy Theory **O**f **E**verything (**TOE**)

- Hydrodynamics states that the response of the fluid to slowly varying perturbations is completely determined by conservation laws (energy, momentum, charge, ...)



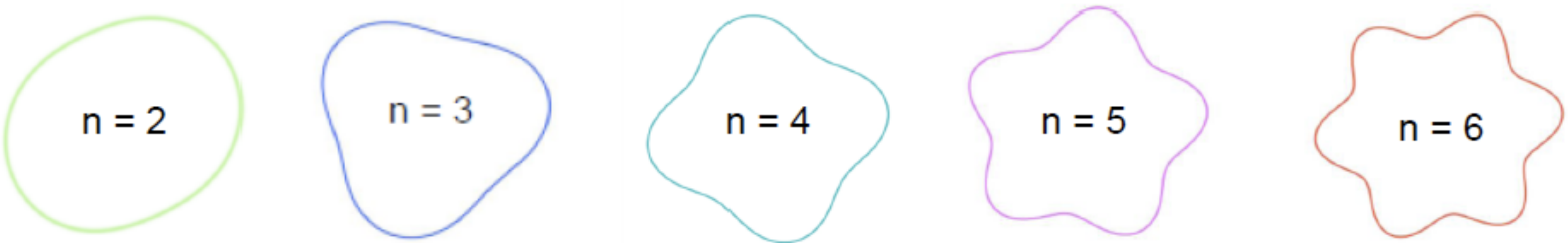
Little Bang

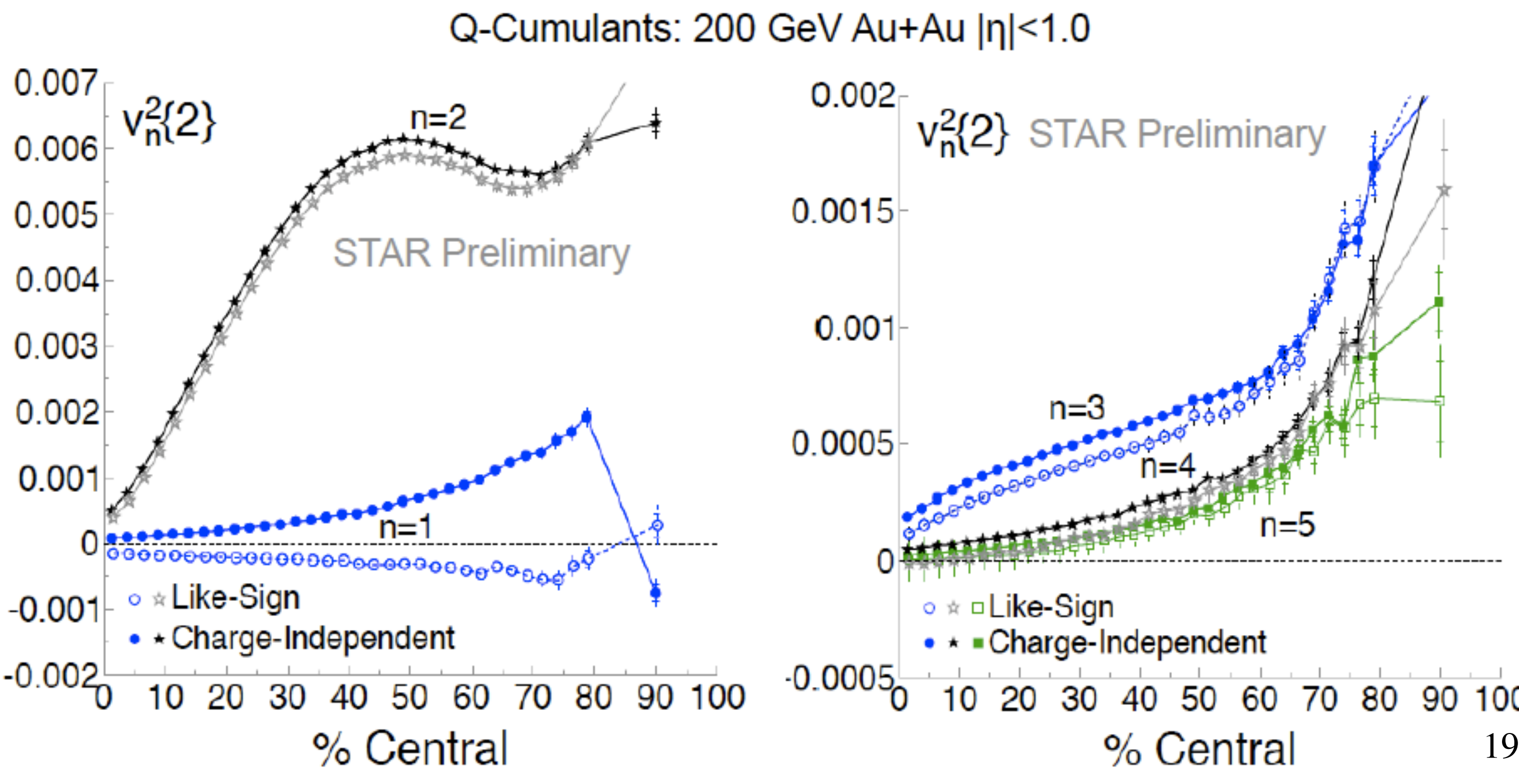


Big Bang

Hydrodynamics

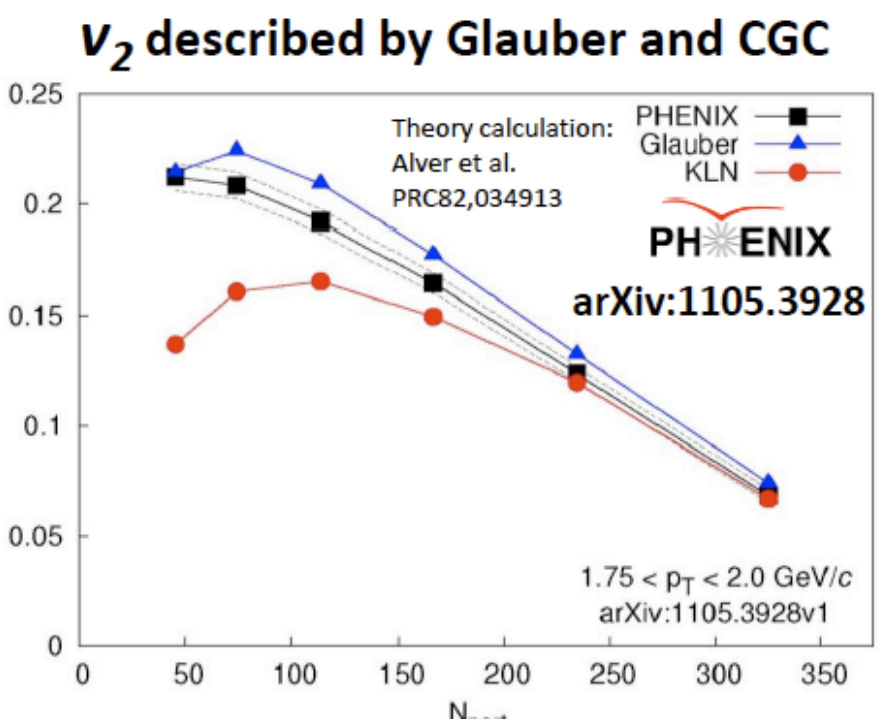
$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

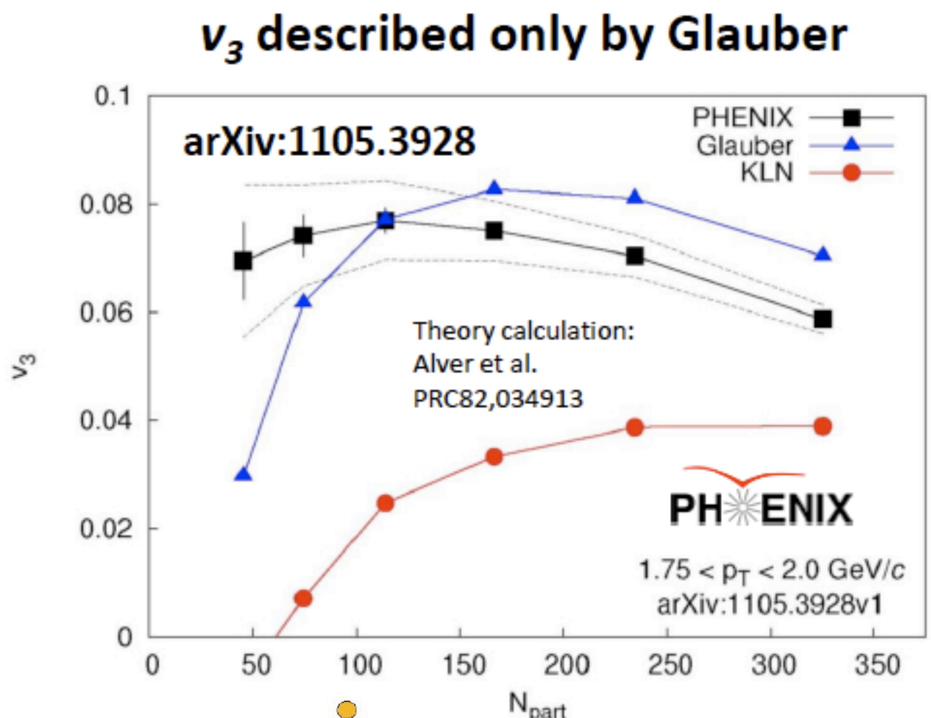




P. Sorensen
[STAR]
QM 2011

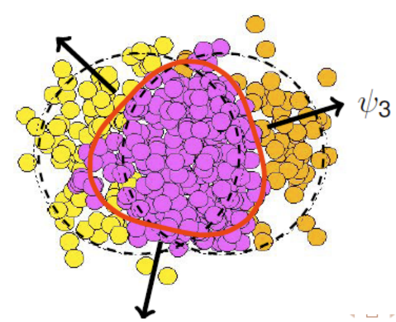
Higher harmonics: discriminate between various initial conditions, extract viscosities





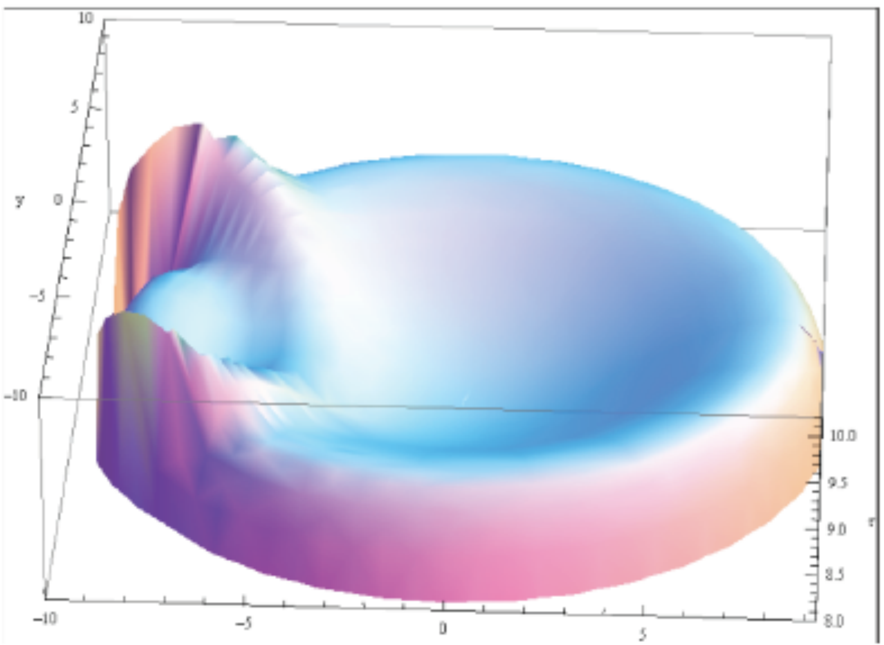
Talks by S. Bathe, R. Lacey [PHENIX] QM 2011

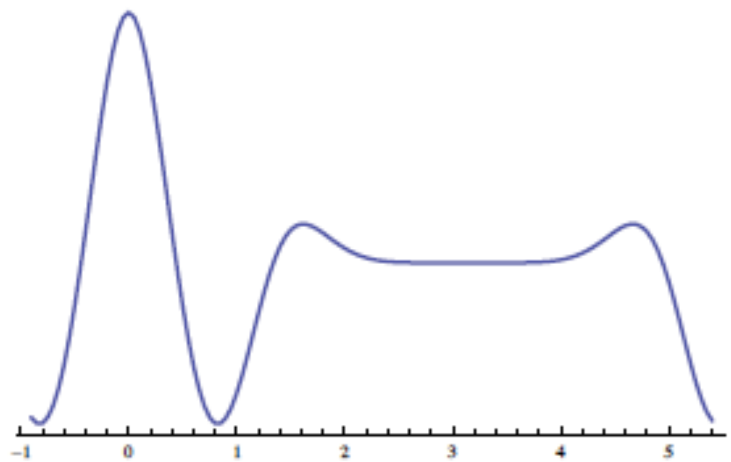
Lack of "chunkiness" in the CGC/KLN MC implementation? ongoing work



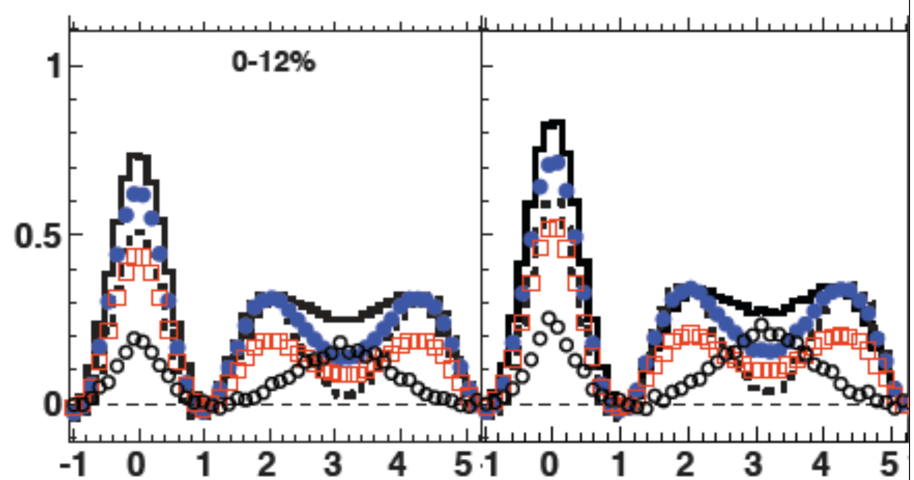
Talks by U. Heinz D. Teaney A.Taranenko

Sonic horizon in the QCD fluid





P. Staig and E. Shuryak, arXiv:1105.0676

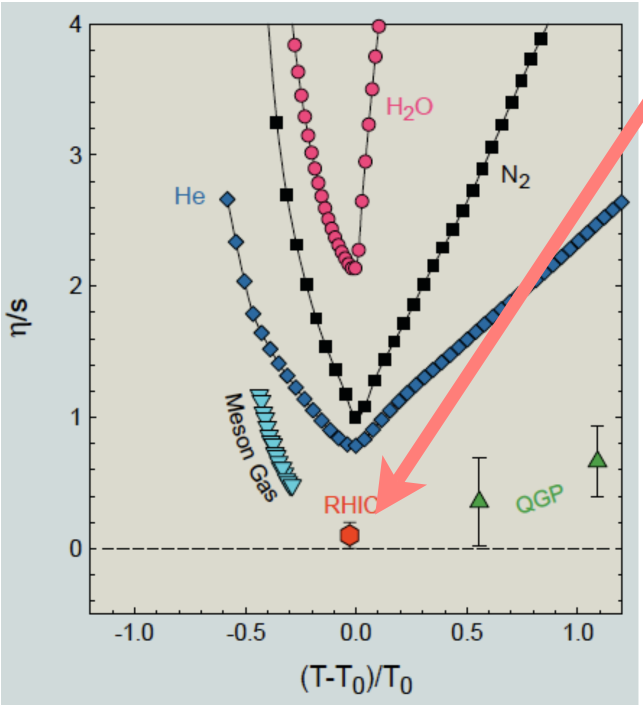


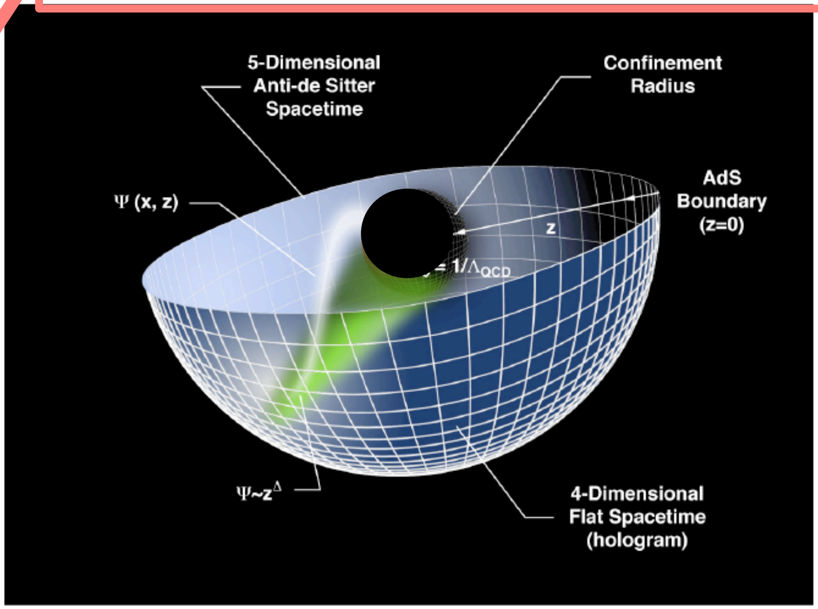
Fluctuation in the initial condition,
so can be long-range in rapidity (causality) -
e.g. due to glasma field flux tubes; hydro -> MagnetoHydroDynamics?

Quantifying the transport properties of QCD matter

- Hydrodynamics:
  an effective low-energy theory, expansion in the ratio of thermal length 1/T to the typical variation scale L, $\epsilon \equiv \frac{1}{LT}$
- Each term in this derivative expansion is multiplied by an appropriate transport coefficient

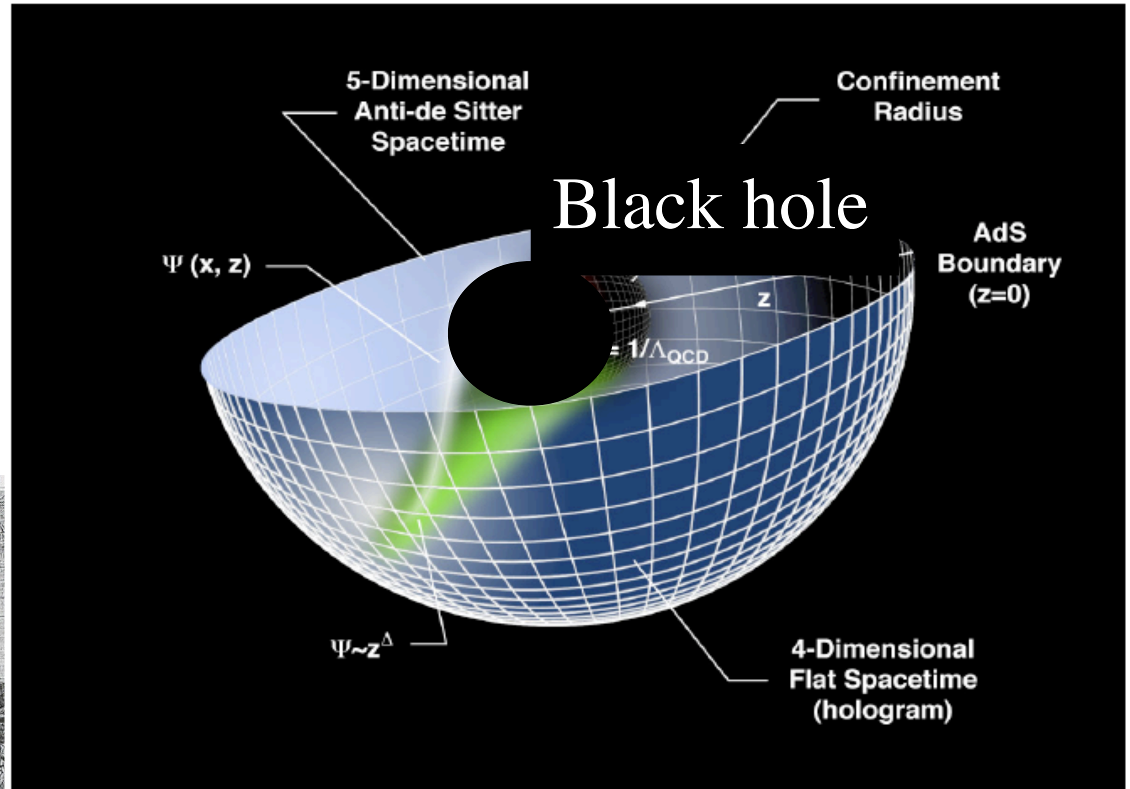
very small shear viscosity - "perfect liquid"; strong coupling





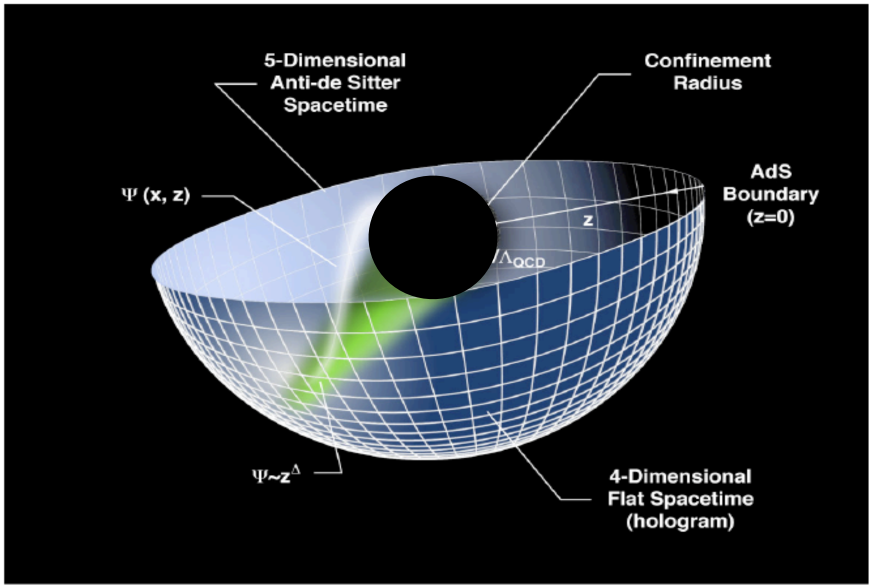
The metaphor of the cave, 2011 A.D.:

AdS/CFT correspondence



“The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard.”

Low-energy effective ToE: hydrodynamics



Holographic view:

Particle contents of supergravity:
gravitons, dilatons, axions
= fields on the boundary

Caveman's view:

- Shear viscosity
- Bulk viscosity

Deviation from conformal symmetry

- Rate of topological transitions

AdS$_5$ "Reality":

- Graviton propagation
- Dilaton propagation
- Axion propagation

Relativistic hydrodynamics and quantum anomalies

- Hydrodynamics: an effective low-energy TOE. States that the response of the fluid to slowly varying perturbations is completely determined by conservation laws (energy, momentum, charge, ...)
- Conservation laws are a consequence of symmetries of the underlying theory
- What happens to hydrodynamics when these symmetries are broken by quantum effects (anomalies of QCD and QED)?

Anomaly-induced currents: the chiral magnetic effect

$$\vec{J} = \boxed{\frac{e^2}{2\pi^2}\ \mu_5}\ \vec{B}$$

P-odd
T-odd

P-even
T-odd

P-odd

P-odd effect!

T-even

Non-dissipative current!

(quantum computing etc)

cf Ohmic conductivity:

$$\vec{J} = \sigma \vec{E}$$

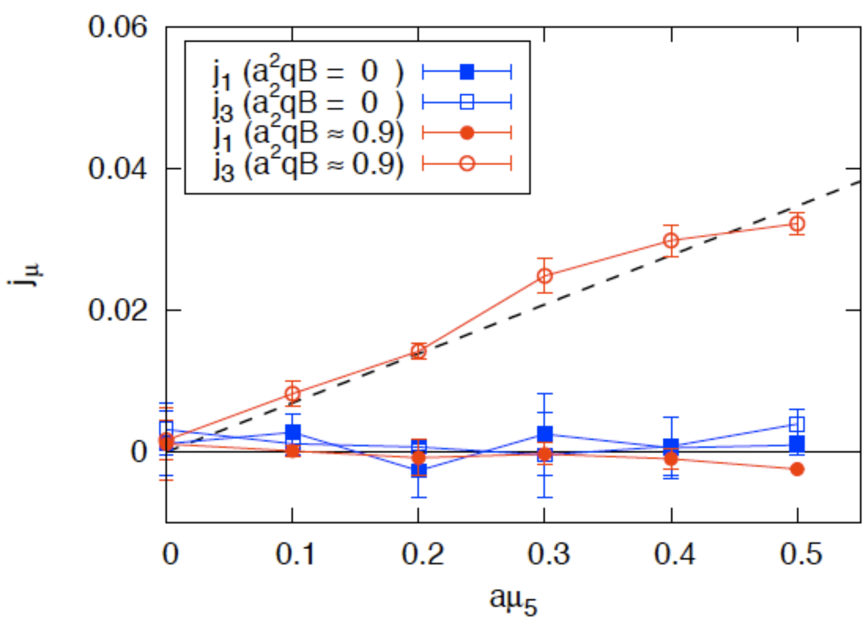
T-odd, dissipative

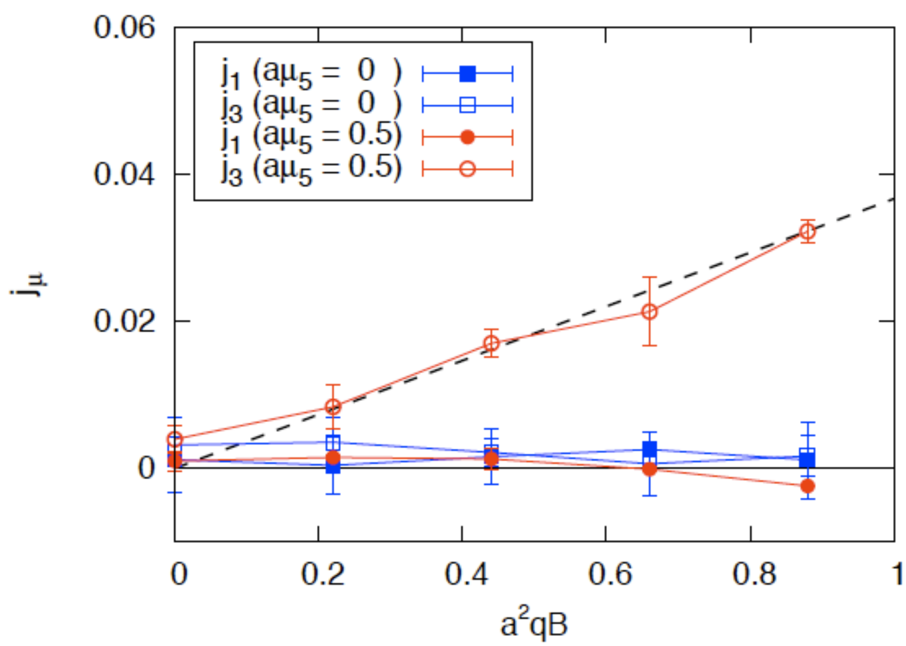
arXiv:1105.0385

Chiral magnetic effect in lattice QCD with chiral chemical potential

Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
(Dated: May 3, 2011)

We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic field to this system, we obtain a finite induced current along the magnetic field, which corresponds to the chiral magnetic effect. The obtained induced current is proportional to the magnetic field and to the chiral chemical potential, which is consistent with an analytical prediction.





Phase diagram in the (T, μ_5) plane? (no sign problem - ongoing)

Chiral MagnetoHydroDynamics (CMHD) - relativistic hydrodynamics with triangle anomalies and external electromagnetic fields

First order (in the derivative expansion) formulation:
D. Son and P. Surowka, arXiv:0906.5044

Constraining the new anomalous transport coefficients:
positivity of the entropy production rate, $\partial_\mu s^\mu \geq 0$

$$\nu^\mu = -\sigma T P^{\mu\nu} \partial_\nu \left(\frac{\mu}{T} \right) + \sigma E^\mu + \xi \omega^\mu + \xi_B B^\mu,$$

CME
(for chirally imbalanced matter)

$$s^\mu = s u^\mu - \frac{\mu}{T} \nu^\mu + D\omega^\mu + D_B B^\mu,$$

$$\xi = C \left(\mu^2 - \frac{2}{3} \frac{n\mu^3}{\epsilon + P} \right), \quad \xi_B = C \left(\mu - \frac{1}{2} \frac{n\mu^2}{\epsilon + P} \right).$$

Anomalous terms in hydrodynamics: dictated by 2nd law of thermodynamics!

FLUID MECHANICS

Second Edition

by

L. D. LANDAU and E. M. LIFSHITZ

Institute of Physical Problems, U.S.S.R. Academy of Sciences

Volume 6 of Course of Theoretical Physics
Second English Edition, Revised

Translated from the Russian by
J. B. SYKES and W. H. REID

XV. RELATIVISTIC FLUID DYNAMICS

133. The energy-momentum tensor
134. The equations of relativistic fluid dynamics
...
137. Anomalies in relativistic fluids

should be added to the next editions of hydrodynamics textbooks ...
motivated by RHIC, and should be studied!

Chiral MagnetoHydroDynamics (CMHD) - relativistic hydrodynamics with triangle anomalies and external electromagnetic fields

First order hydrodynamics has problems with causality and is numerically unstable, so second order formulation is necessary;

Complete second order formulation of CMHD:
DK and H.-U. Yee, 1105.6360

Many new transport coefficients - use conformal/Weyl invariance; still 18 independent transport coefficients related to the anomaly. 15 that are specific to 2nd order; 13 are computed (**T-invariance!**)

new

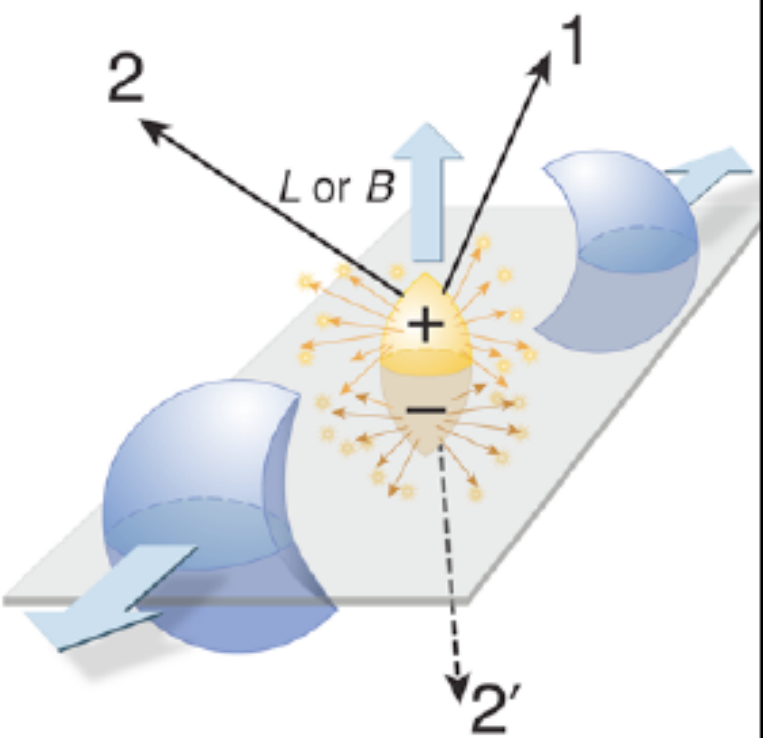
$$
\begin{aligned}
&\sigma^{\mu\nu}\mathcal{D}_\nu\bar{\mu}\ ,\ \omega^{\mu\nu}\mathcal{D}_\nu\bar{\mu}\ ,\ \Delta^{\mu\nu}\mathcal{D}^\alpha\sigma_{\nu\alpha}\ ,\ \Delta^{\mu\nu}\mathcal{D}^\alpha\omega_{\nu\alpha}\ ,\ \sigma^{\mu\nu}\omega_\nu\ ,\\
&\sigma^{\mu\nu}E_\nu\ ,\ \sigma^{\mu\nu}B_\nu\ ,\ \omega^{\mu\nu}E_\nu\ ,\ \omega^{\mu\nu}B_\nu\ ,u^\nu\mathcal{D}_\nu E^\mu\ ,\\
&\epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha\mathcal{D}_\beta\bar{\mu}\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu B_\alpha\mathcal{D}_\beta\bar{\mu}\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha B_\beta\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha E_\beta\ ,\ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha B_\beta\ .
\end{aligned}
\tag{2.60}
$$

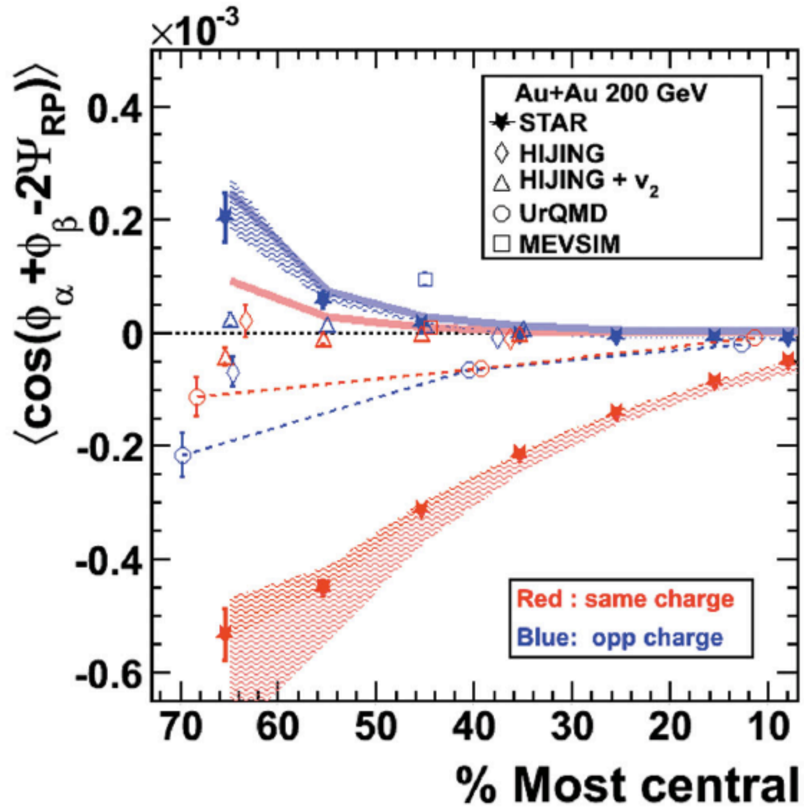
Many new anomaly-induced phenomena!

PRL 103, 251601 (2009)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

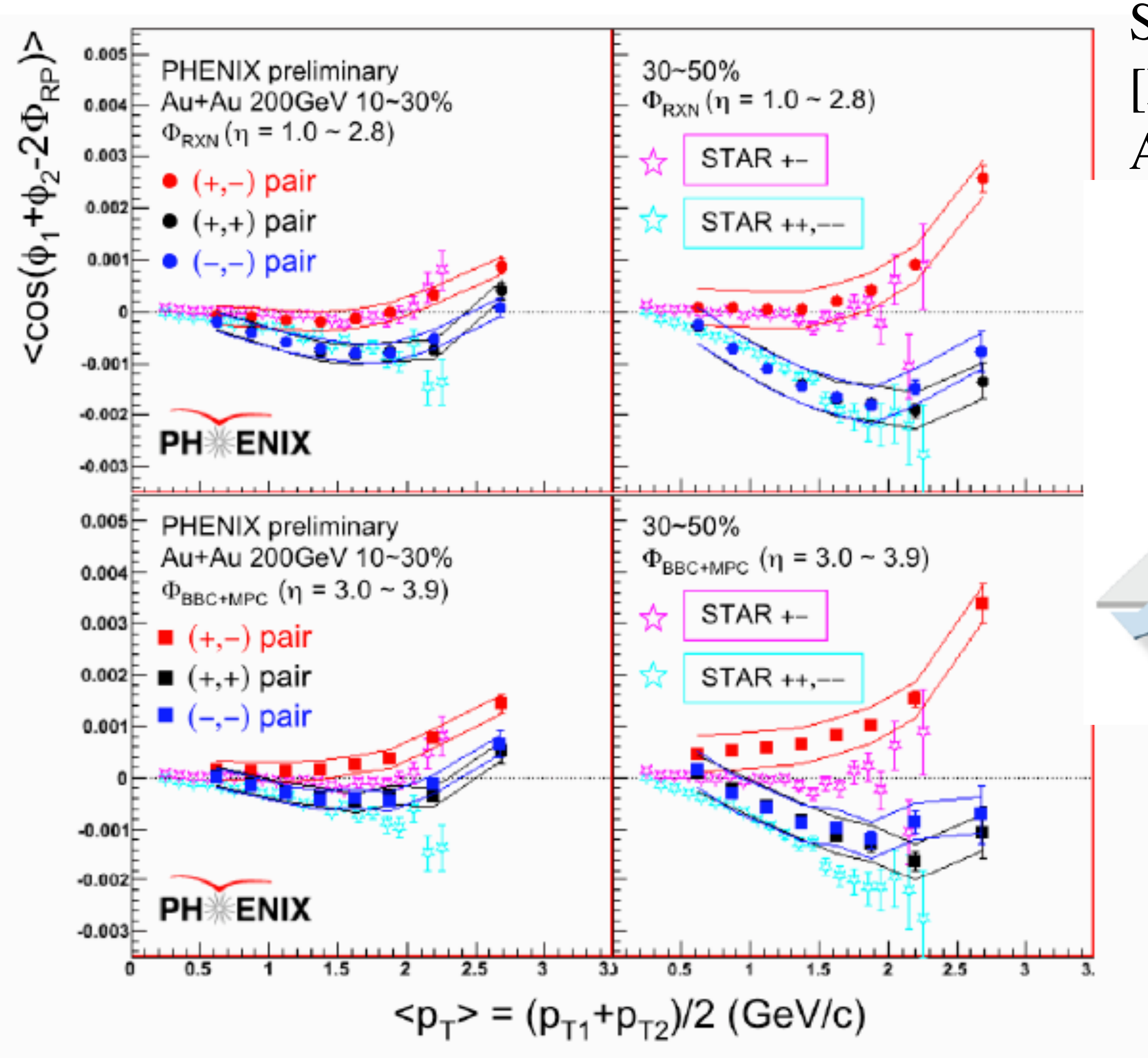
(STAR Collaboration)



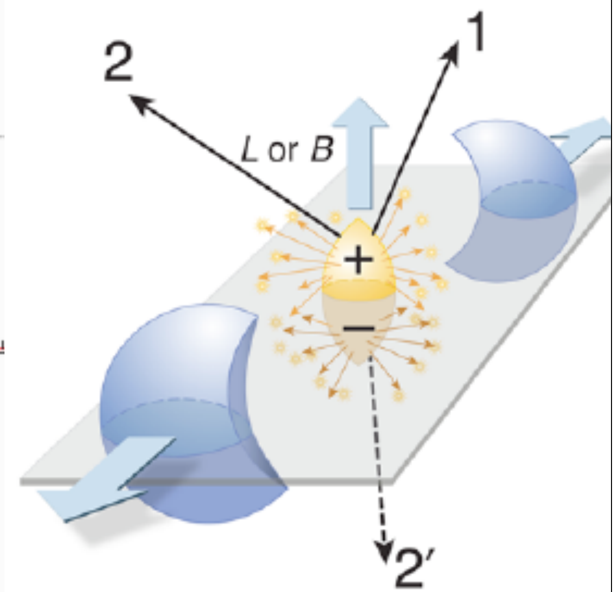


NB: P-even quantity (strength of P-odd fluctuations); consistent with the measured balance functions (dynamical charge correlations) - e.g. D.Gangadharan[STAR] QM’11

Talk by J. Dunlop



S.Esumi et al
[PHENIX Coll]
April 2010



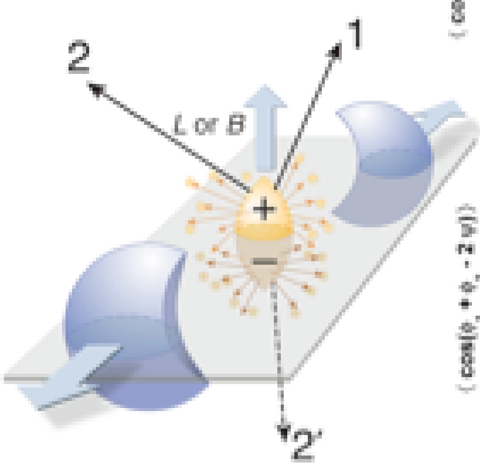
Relatively good agreement between PHENIX & STAR

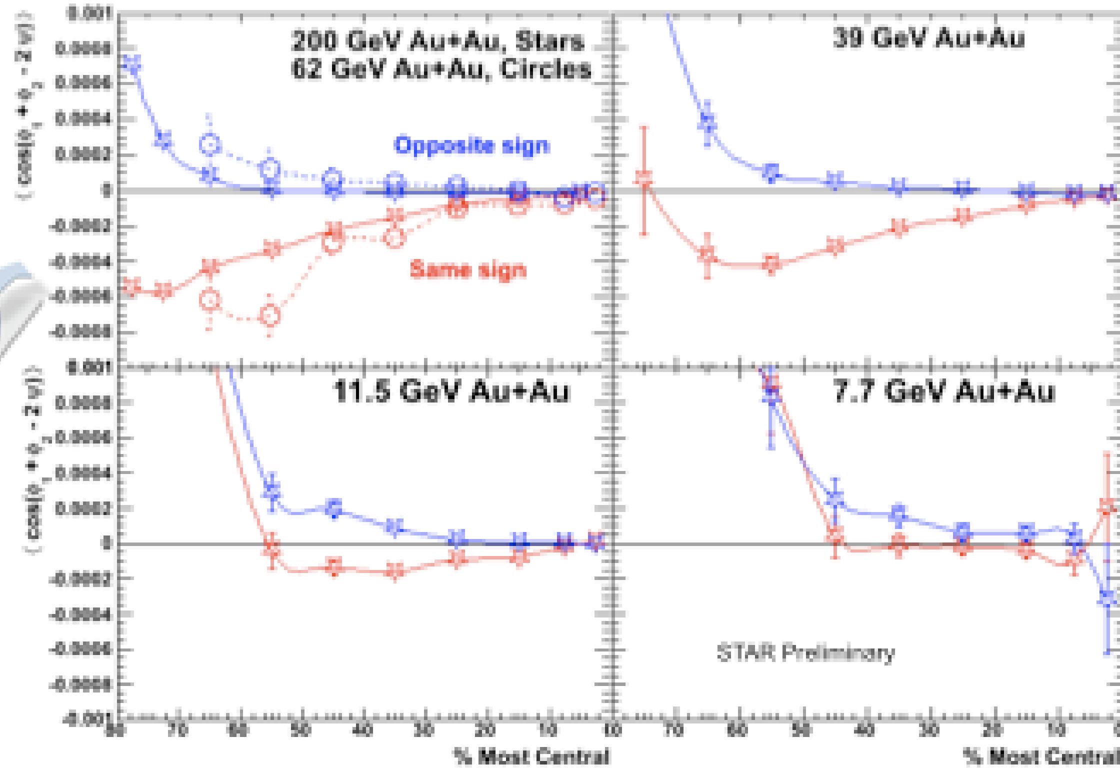
B. Mohanty [STAR Coll] QM 2011

Dynamical Charge Correlations

Observations:

Measurement of charge correlations with respect to event plane

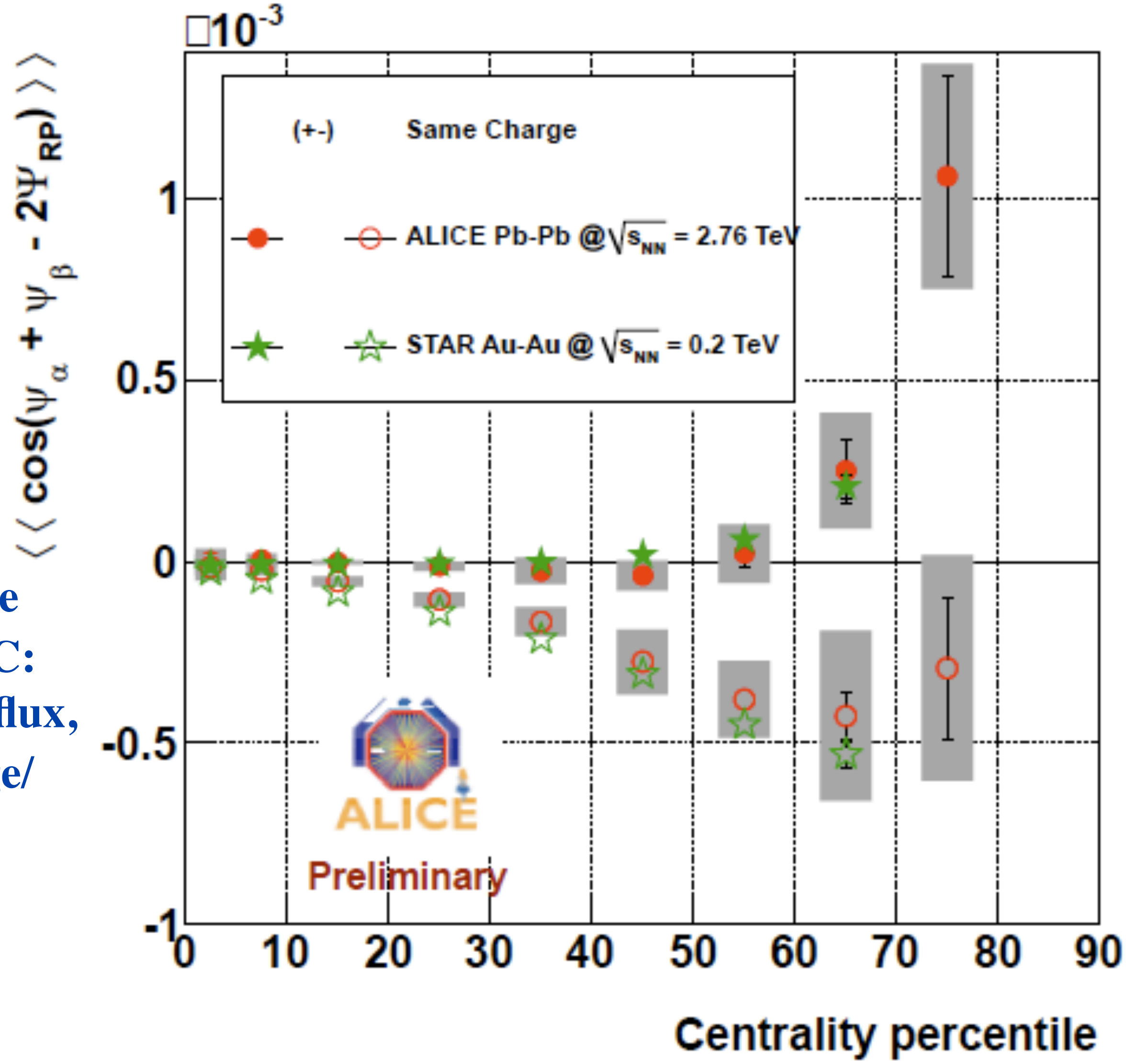




Difference between same sign and opposite sign charge correlations decreases as beam energy decreases.
Same sign charge correlations become positive at 7.7 GeV.

Signal disappears; onset of deconfinement?

CME studies at the LHC

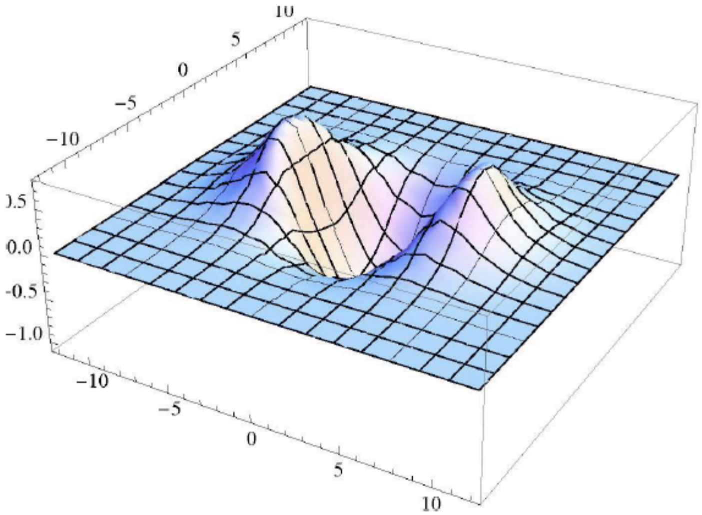


Same magnitude at RHIC & LHC: same magnetic flux, same top. charge/ particle density ratio

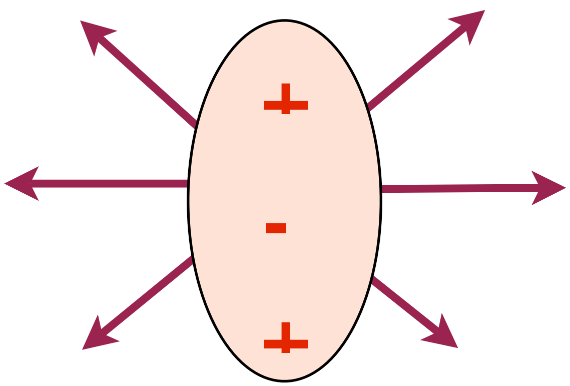
Talk by J. Harris

+ 2 particle correlations - out-of-plane?

P. Cristakoglou et al [ALICE Coll] arXiv:1106.2826

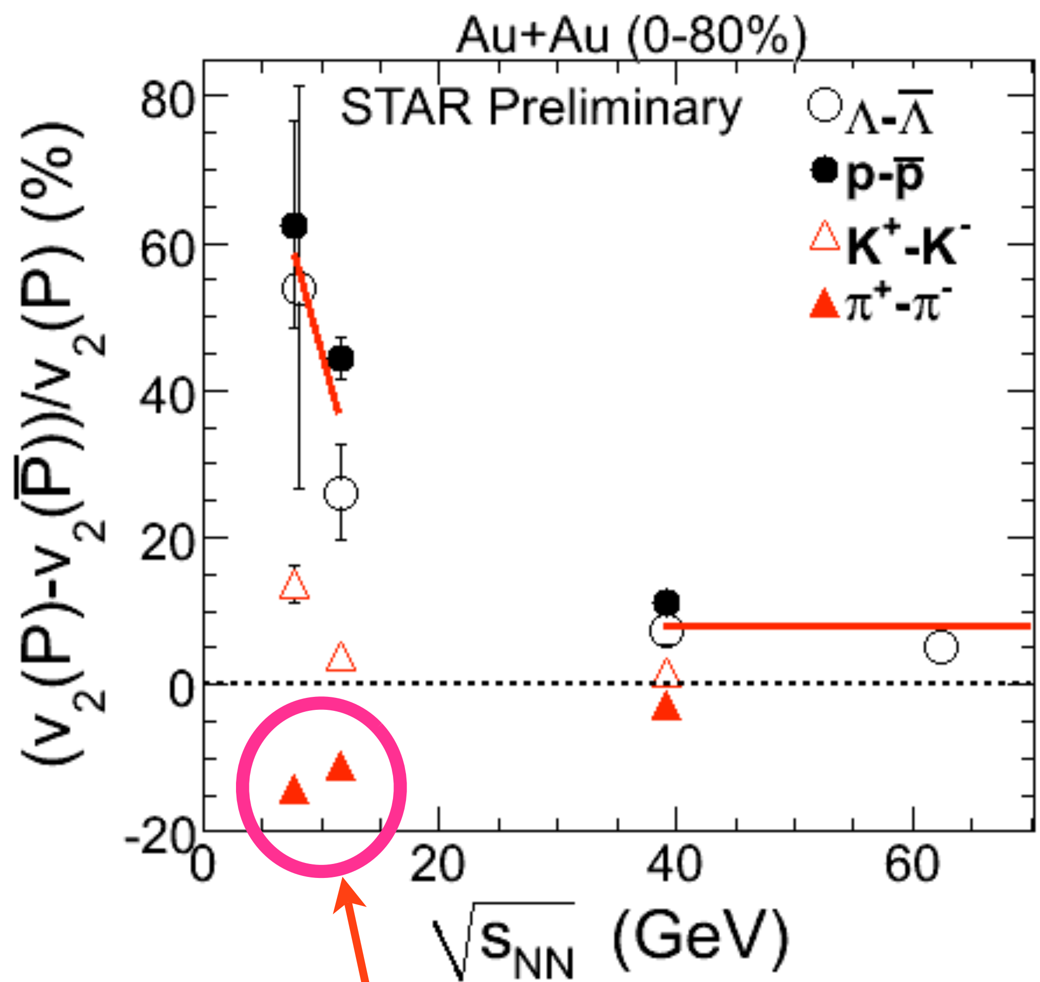


Y.Burnier, DK, J. Liao, H.-U.Yee,
arXiv:1103.1307 - PRL



Anomaly-induced quadrupole moment **at finite baryon density**

B.Mohanty [STAR] Quark Matter 2011



Chiral magnetic wave or
a mundane effect (Coulomb, resonances)?

A new test: baryon asymmetry

DK, D.T.Son
arXiv:1010.0038; PRL

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}\left[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB) 2\mu\vec{\omega}\right]$$

CME

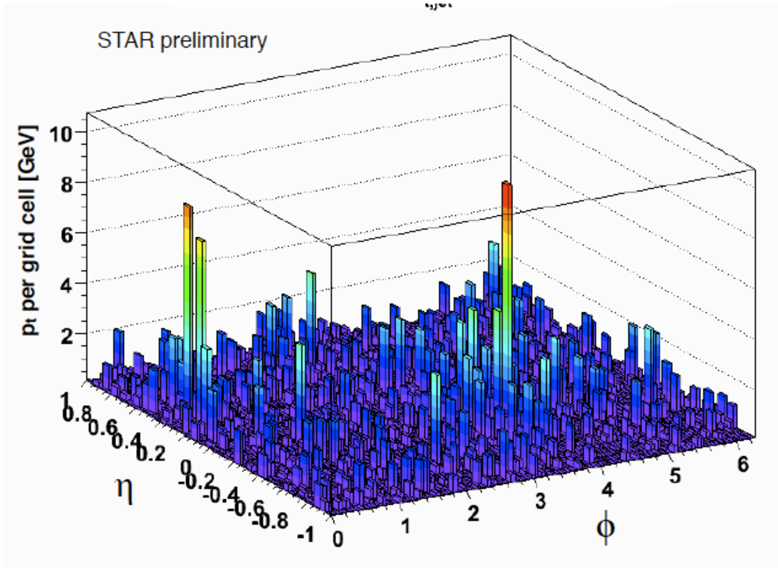
Vorticity-induced
"Chiral Vortical Effect"

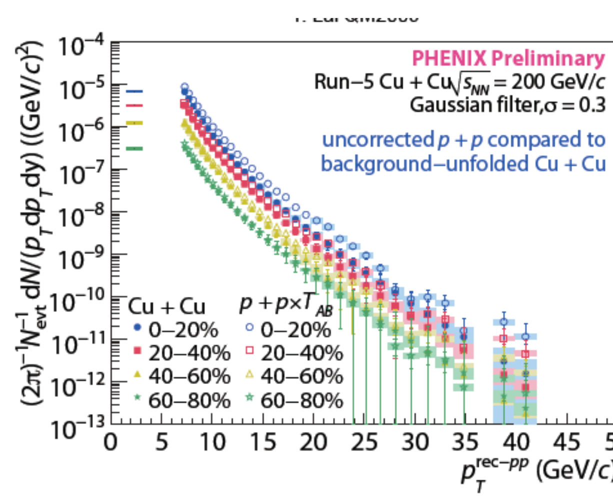
There has to be a **positive correlation between electric charge and baryon number!** mixed correlators - e.g. $\Lambda \; \pi^+$

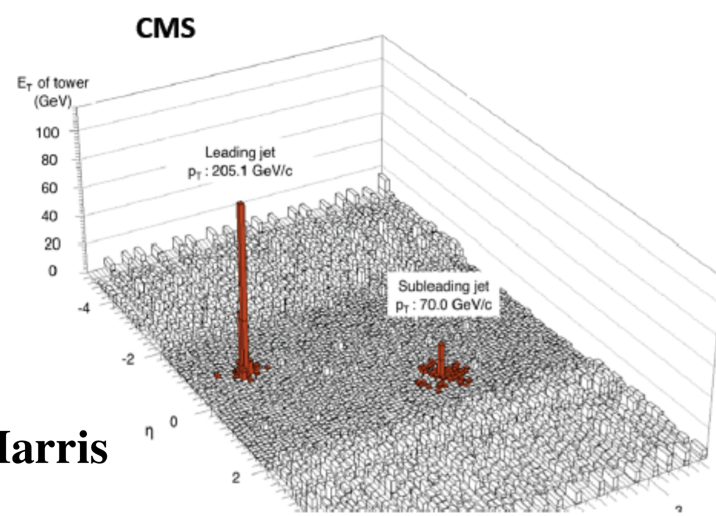
Control over magnetic field - use **U+U collisions**
separate eccentricity and elliptic flow from the magnetic field effects

Talk by J. Dunlop

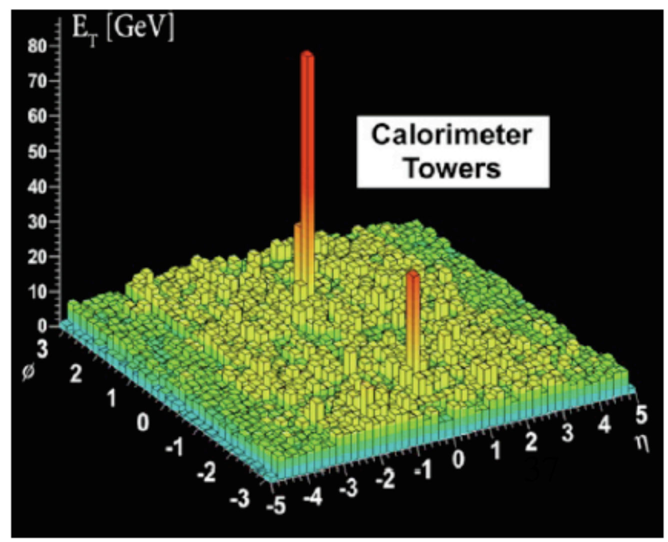
Response of QCD fluid to fast collimated perturbations (**jets**)







ATLAS

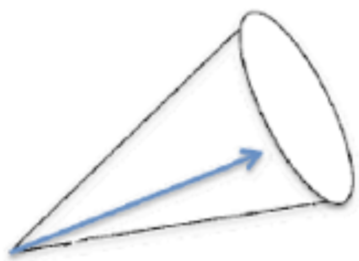


Talk by J. Harris

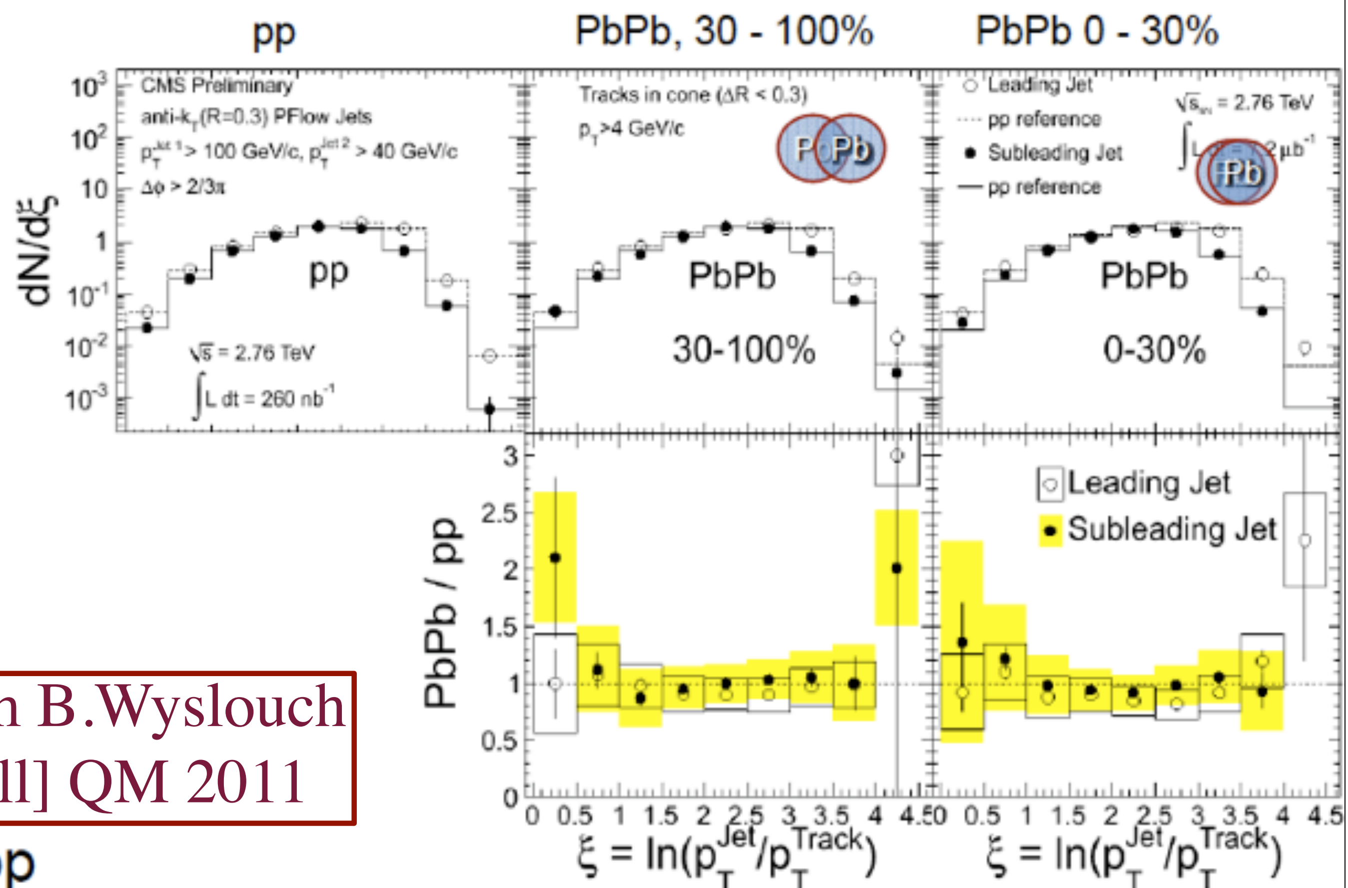
Jets at LHC: suppressed, but shape unmodified?

Updated jet algorithm: Particle Flow, Anti-k_T, R=0.3

Charged tracks, p_T^{Track} >4 GeV/c, jets with p_T^{Jet} =40-300 GeV/c



$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$



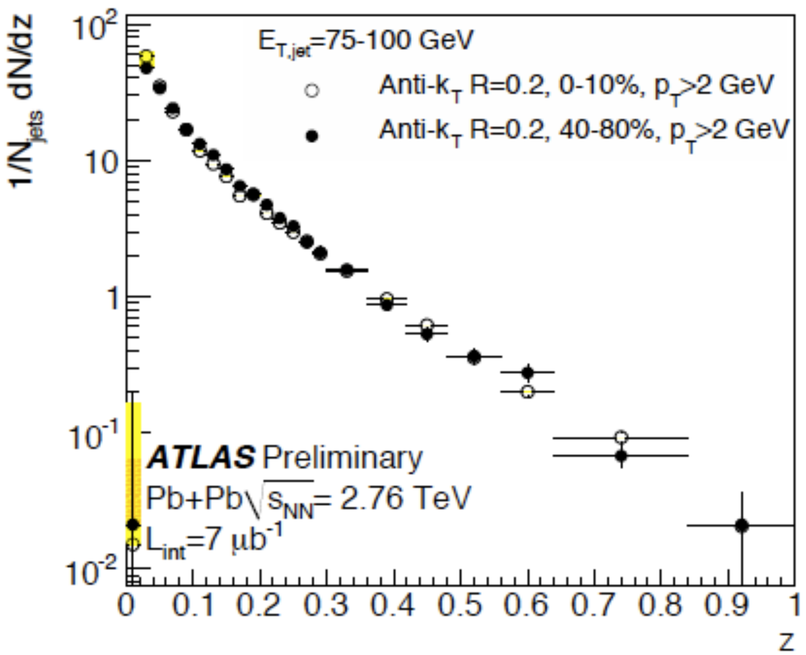
Slide from B.Wyslouch [CMS Coll] QM 2011

Compare PbPb to pp

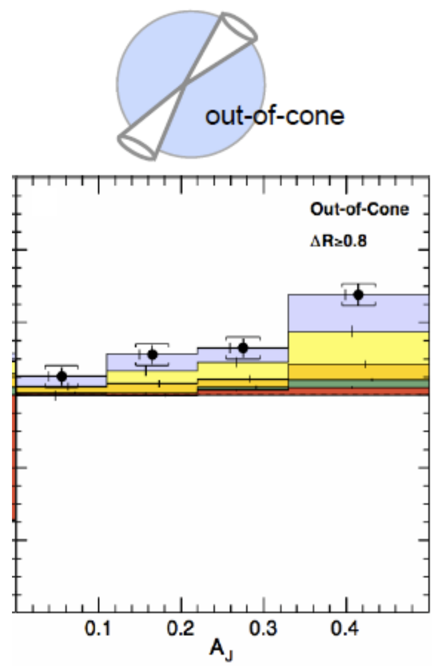
– Fragmentation function similar between PbPb and pp

Jets in QCD matter: suppressed, but shape unmodified?

No change in shape between central and peripheral collisions



P.Steinberg [ATLAS Coll] QM 2011



Out-off-cone low p_T particles balance the complete event

B. Wyslouch [CMS Coll] QM 2011

Theoretical approaches: talk by X.N.Wang

Formation time of gluon radiation

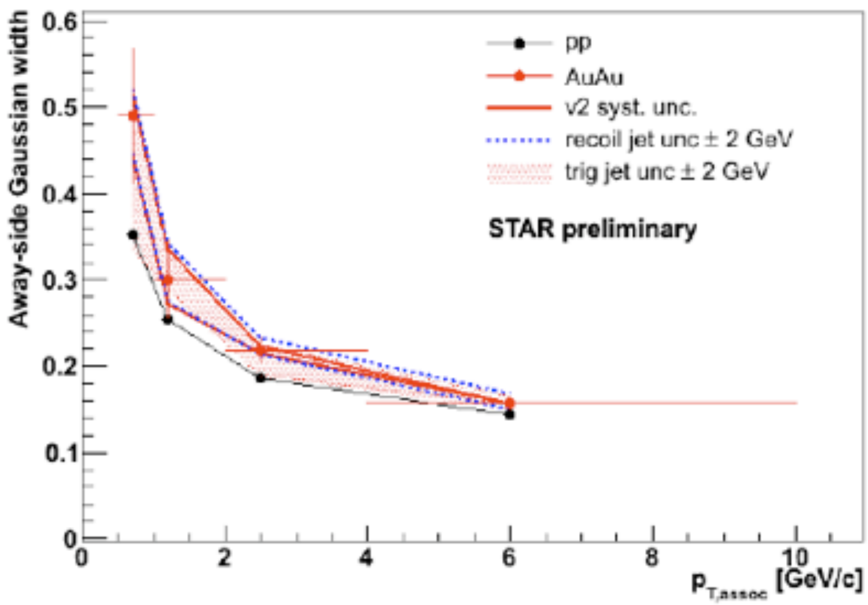
$$t_f \sim \frac{\omega}{k_\perp^2} \sim \frac{1}{k_\perp}\frac{1}{\theta}$$

- do not expect modification at small angle, large z;
but: surprise at small z, large angles

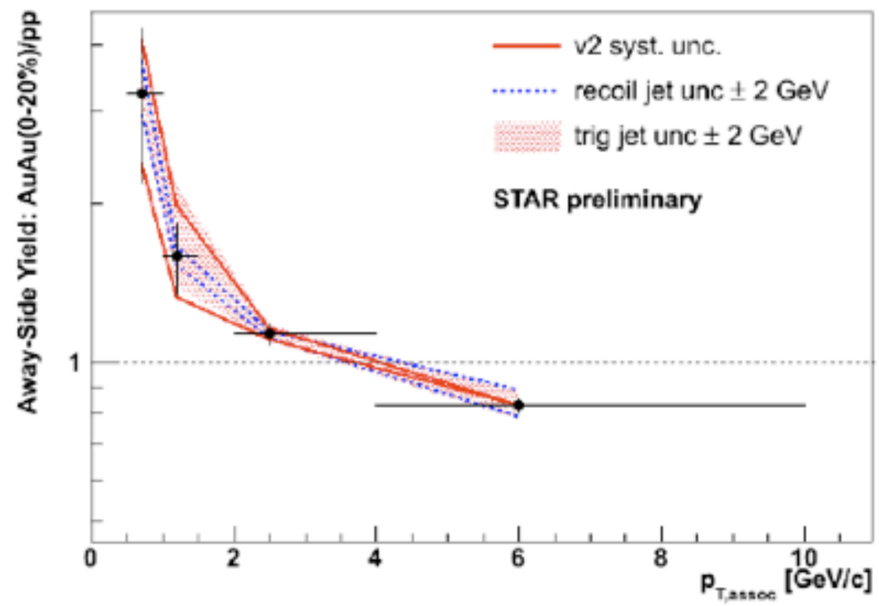
Jet shape at RHIC

Measure jet-hadron correlations <u>with</u> the requirement of a fully reconstruct recoil jet:

Away-side width



Away-side I_{AA}



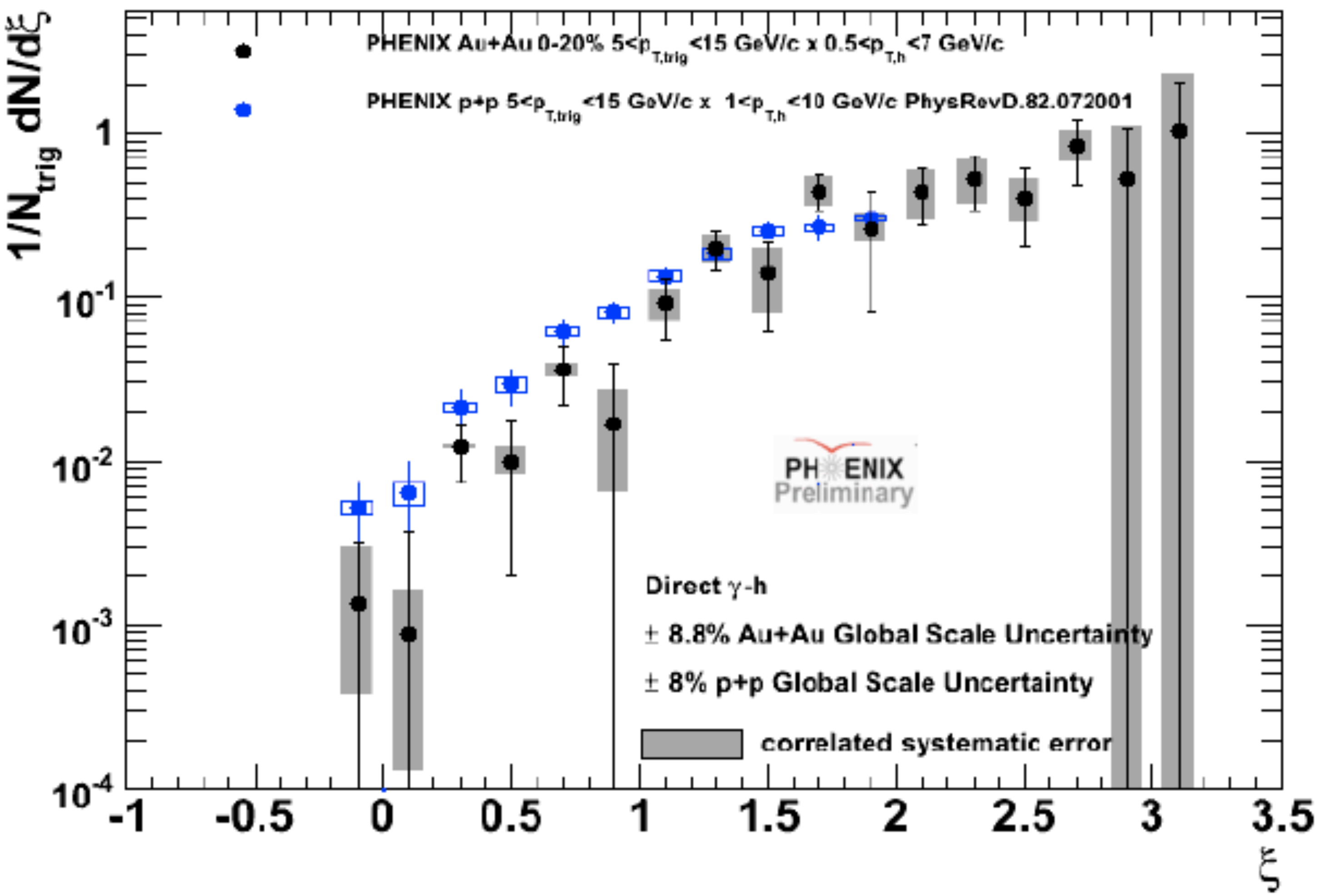
Away-side shows broadening and softening in jet-hadron correlations

⇒ **Highly biased jets (p_T^{Cut}>2 GeV) seem to be modified;
jet-finding algorithm not only reconstructing unmodified jet!**

⇒ **Suppression of di-jet coincidence most likely due to "out-of-cone energy"**

Slide from J. Putschke [STAR]

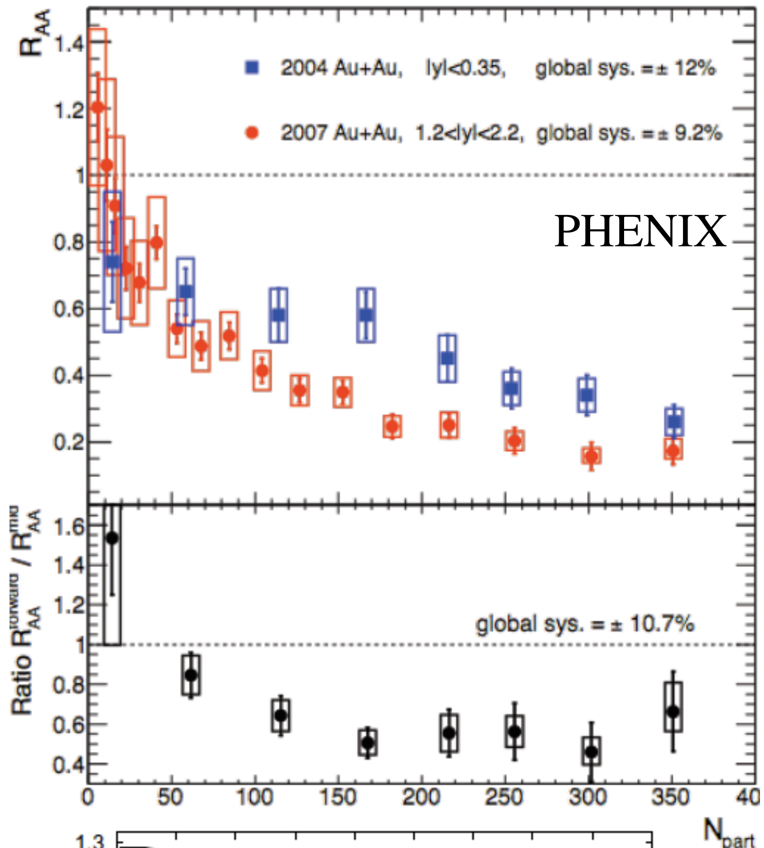
Jet shape at RHIC: γ-tagged jets



Jet softening?

Talk by M. Purschke [PHENIX], QM’2011

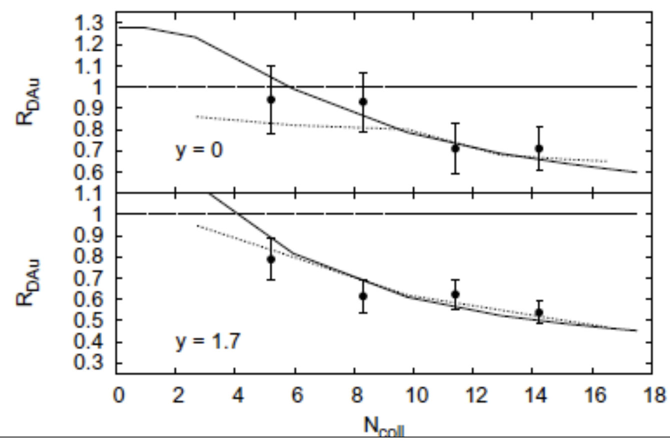
Quarkonium suppression at RHIC



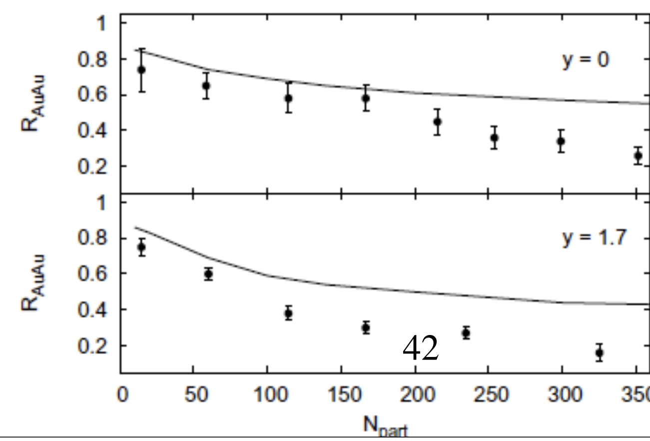
the observed AA suppression cannot be explained by cold nuclear matter effects alone;
however these effects are non-linear and strongly depend on x, centrality, ...

gluon saturation -
talk by M. Nardi

d Au



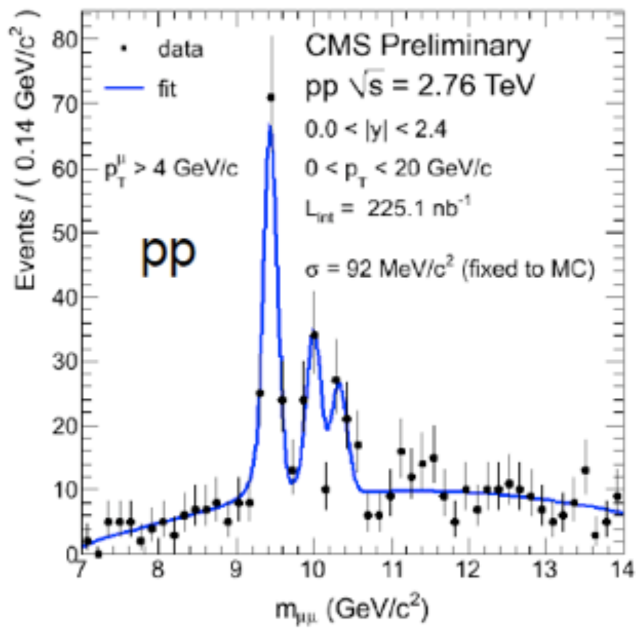
Au Au

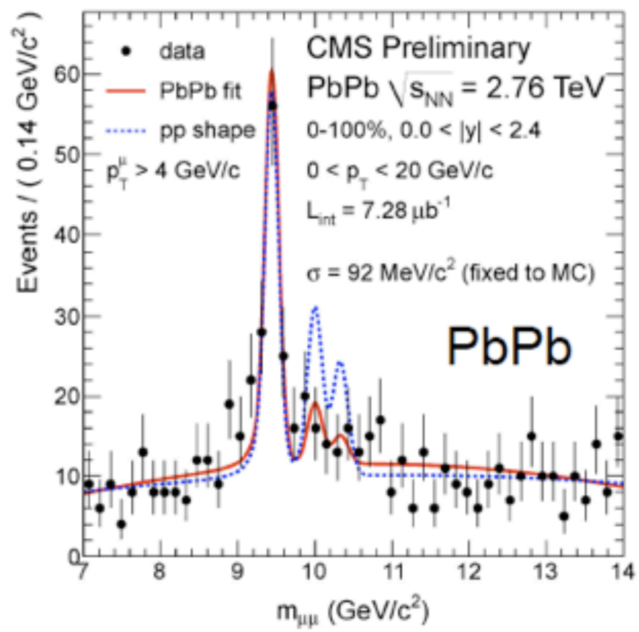


The plasma thermometer: quarkonium suppression

Bottomonium studies at RHIC have already begun; +upgrades

Suppression of excited Υ states





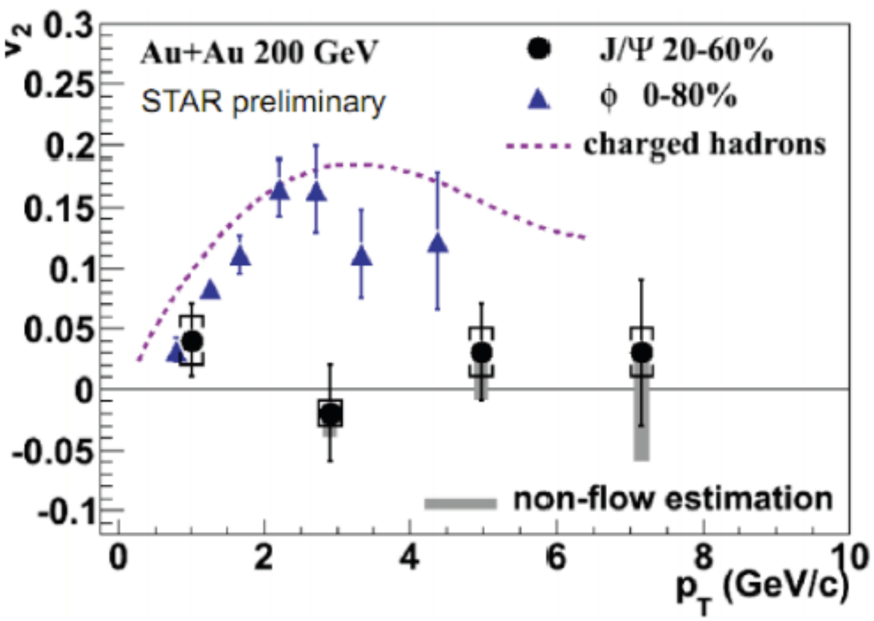
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

Slide from B.Wyslouch [CMS Coll] QM 2011

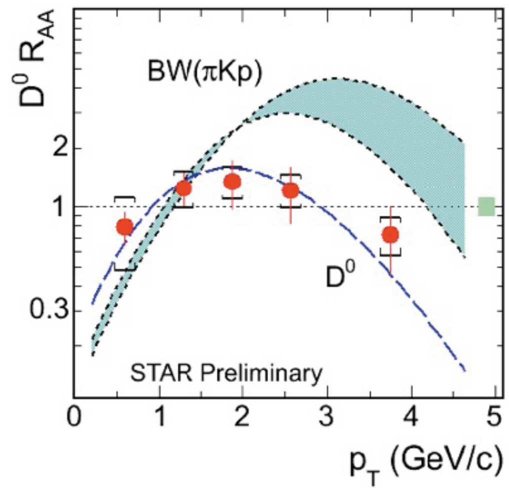
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Excited states Υ(2S,3S) relative to Υ(1S) are suppressed

Heavy quark transport and energy loss

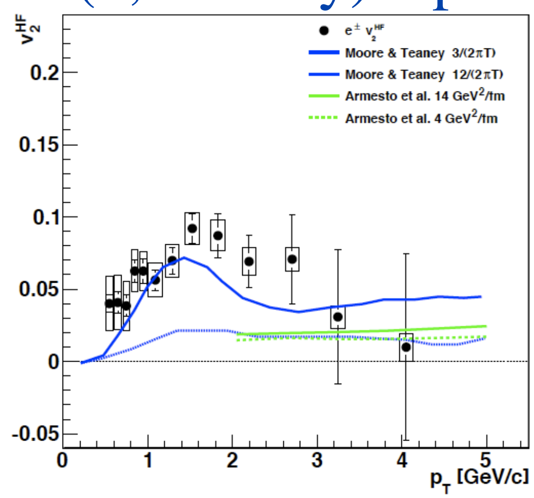


J/ψ does not flow...



STAR
Talk by
Y.Zhang

does open charm ?
(c, b decay) leptons:



PHENIX
arXiv:1005.1627

Talks by J. Dunlop, M. Leitch **need vertex detector measurements at RHIC!**

Understanding the dynamics of gauge fields with heavy ions

Physics		RHIC measurements
❑ Weak/vacuum fields	↔	❑ Jets, parton fragmentation in pp
❑ Strong static fields	↔	❑ Small x distributions in nuclei
❑ Real-time dynamics	↔	❑ EM probes, jets, heavy quarks
❑ Gauge fields with boundary conditions/ event horizons	↔	❑ Bulk behavior, soft photons and dileptons
❑ Low-energy effective Theory of Everything: hydrodynamics	↔	❑ Transport properties: flow harmonics, correlations
❑ Topology of gauge fields; Chiral MagnetoHydroDynamics	↔	❑ Charge-dependent flow harmonics, charge-baryon number correlations, U+U

Summary

Heavy ion program at RHIC opens a window into the dynamics of gluon fields and QCD matter under extreme conditions

Complementarity with LHC program, and many unique possibilities (BES - finite baryon density, CP, spin,...)

The future: quantitative characterization of transport properties of QCD fluid, phase diagram, novel phenomena